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ELECTRON OPTICAL SYSTEMS AND THEIR APPLICATIONS

By V. K. ZWORYKIN, Ph.D.

(*Lecture delivered before the* WIRELESS SECTION, *5th February*, 1936.)

PART I
ELECTRON OPTICS OF IMAGE FORMATION

The beginnings of electron optics can almost be said to pre-date the discovery of the electron itself. It was well known to the earliest investigators that an object in the path of a cathode-ray beam would cast a sharp shadow on a fluorescent screen which was bombarded by these rays. In this respect at least it was known that cathode rays resembled light rays.

It was not long after the discovery of the electron itself that such workers as Busch, Glaser, and later Knoll and Ruska, began the calculation of electron paths and thus laid the groundwork for the true science of electron optics. Since that time these trajectories have been studied in increasing detail as the importance of electron optics has become more and more widely recognized.

Of particular interest is the calculation of the paths through fields having radial symmetry. This type of field, either electrostatic or magnetic, can be shown to cause the electron paths to bend in a manner similar to the way in which light is bent when going through a lens. It is this possibility of replacing an electronic system by an analogous optical lens system that gives my subject its name, and this replacement by an optical analogue often (but not always) simplifies both qualitative and quantitative study of an electron " lens " system.

The behaviour of electrons passing through an aperture at potential V from a region of field strength ϵ_1 into a region of field strength ϵ_2 illustrates the similarity between electron rays and light rays. In this case the aperture will cause the electrons to converge just as would a spherical lens of focal length $f = 4V/(\epsilon_2 - \epsilon_1)$. Just as the glass lens will produce an image of a light source, so will the aperture be capable of producing an electron image. Furthermore, it has been shown that any cylindrical symmetrical configuration of an electrostatic field will produce either a positive or a negative lens action if the electron path is not too far from the axis of symmetry.

It is not my purpose to present a theoretical study of the " optics " of electrons, as there are many excellent articles dealing with the subject, but rather to discuss certain practical details concerning the formation of electron images. Furthermore, I shall limit my discussion to the formation of images by means of electrostatic fields rather than systems involving magnetic lenses or combined magnetic and electrostatic lenses.

If electron optics had been of academic interest only, it would never have received the attention it has. Two of the most important practical applications, and the ones which have been most fully studied, are the electron gun and the electron microscope. The first is characterized by the requirement that a very small electron source is to be focused into a very small image or spot. In this case, both image and object are close to the axis of the lens, and factors such as curvature of the image field, distortion within the image, etc., are not of great importance. A typical example of an electron gun is shown in Fig. 1. This system consists of two lenses (shown in the optical analogue under the diagram of the gun) which produce on the screen an image, not of the cathode itself but of a point close to the cathode (known as the cross-over). This type of electron optics plays an important rôle in cathode-ray oscillographs in general and in cathode-ray television in particular. The latter application has already been described in the *Journal*.* The final results of image reproduction depend almost entirely on the accuracy of electron-beam focusing at both the transmitting and receiving ends. An illustration of the progress in this field is shown in Fig. 2 (Plate 1, facing page 8), which is a photograph of a television image from a moving-picture film reproduced with 343 lines.

The second field of application, the electron microscope, is one in which electron optics is used to produce a very much enlarged image of a small object. Fig. 3 shows a typical electron microscope, illustrated in Brüche and Scherzer's excellent monograph on electron optics. There are a great many types of these microscopes, most of which make use of combined electrostatic and magnetic fields, but a discussion of them is beyond the scope of this lecture.

In the course of a study of electron optics carried out

* V. K. ZWORYKIN: "Television with Cathode-Ray Tubes," *Journal I.E.E.*, 1933, vol. 73, p. 437.

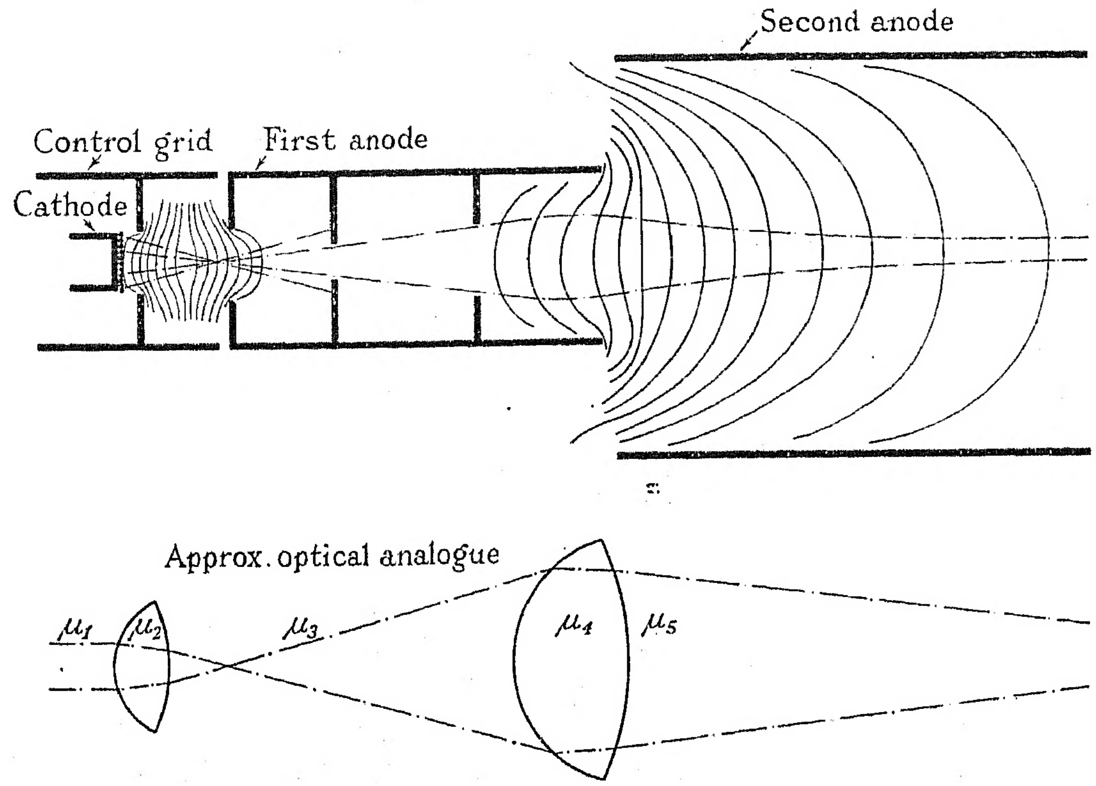

Fig. 1

$\mu_1 > \mu_2 > \mu_3 > \mu_4 > \mu_5$

by the firm with which I am associated, there arose the problem of producing an electron image of an extended object; furthermore, it was necessary to do this solely by electrostatic means. The optical analogue of this system is the lens system of a copying camera. A satisfactory solution of this problem requires that (1) the image be free from distortion, (2) the circle of confusion be small, (3) the effective aperture of the lens large, and (4) the area of the object and image large. The magnification of this system should be close to unity, i.e. from 0·5 to 3.

As a basis for this system, let us consider the field between two coaxial cylinders of equal diameter. Fig. 4 illustrates diagrammatically this type of image tube. The cathode is a semi-transparent photoelectric surface, and the viewing screen is similar to those used in the cathode-ray oscillograph, formed by spreading a thin layer of special willemite on the glass end-plate of the tube. A potential is applied between the two cylinders, the cathode and adjoining cylinder being negative, while the screen and long cylinder are made positive. When a light image is projected on the photocathode, electrons are released in proportion to the intensity of the light falling on any given area. These electrons are focused by the electrostatic lens between the two cylinders into an inverted image on the fluorescent screen.

Since this system is to form the basis of the image tube, it is worth while to examine it in detail, from both a theoretical and an experimental aspect. The potential distribution can be determined using the relations

$$\phi(z) = (\epsilon_2 - \epsilon_1)\frac{2}{\pi}\int_0^\infty \frac{\cos(2ku)\sin(2kz)dz}{kJ_0(jk)}$$

$$\phi''(z) = (\epsilon_2 - \epsilon_1)\frac{8}{\pi}\int_0^\infty \frac{k\cos(2ku)\sin(2kz)dz}{J_0(jk)}$$

$$\frac{d^2r}{dz^2} + \frac{\phi'}{2\phi}\frac{dr}{dz} + \frac{\phi''}{4\phi}r = 0$$

where z = distance along axis, u = distance between cathode and junction of two cylinders, and r = distance measured at right angles to axis. A solution of the differential equation yields the axial potential distribution, which is shown in Fig. 5(a) together with the second derivative of the potential. From these the electron paths can be calculated by means of the well-known ray

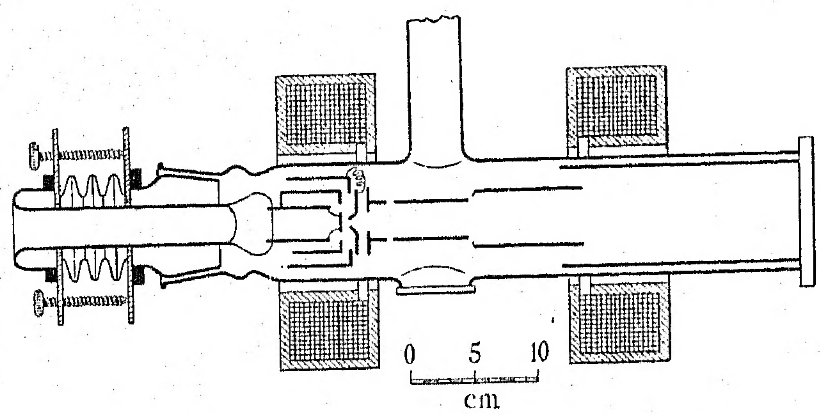

Fig. 3.—Typical electron microscope.

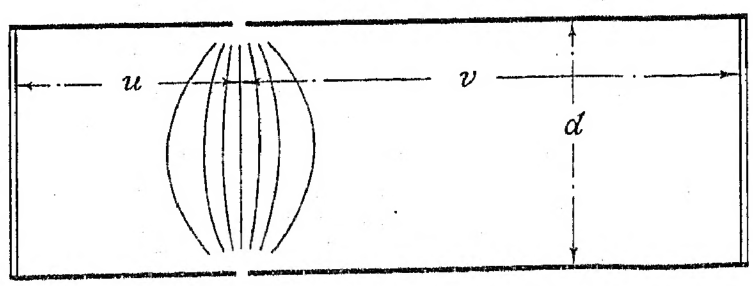

Fig. 4.—Lens system formed by coaxial cylinders.

formula. Fig. 5(*b*) shows the path of an electron leaving the centre of the cathode at an angle to the axis, which gives us the image position; and also the path of an electron leaving the cathode with zero velocity from a point off the axis, giving us the magnification of the system.

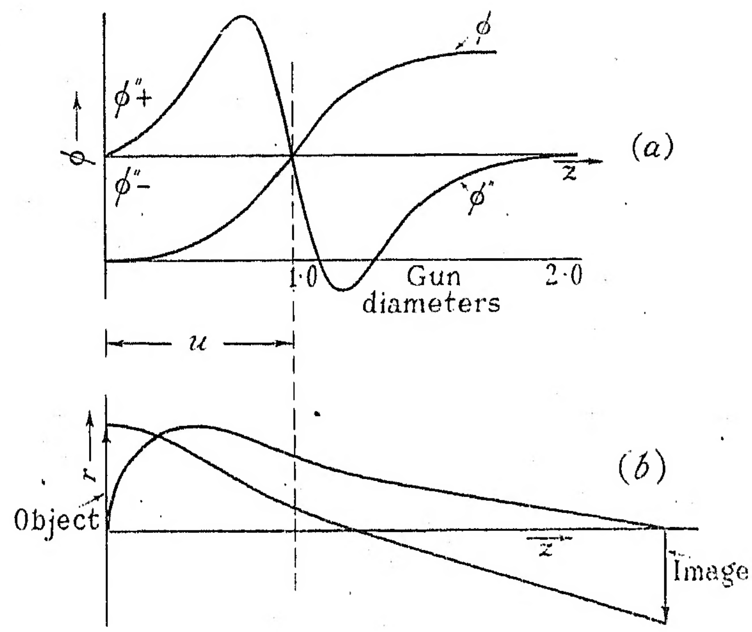

Fig. 5.—Electron paths.

The position of the image is determined by the distance u between the cathode and the junction of the two cylinders, which, for convenience, I shall call the "lens." Determinations of the lens-image distance v in terms of u have been made experimentally also, using a tube having a movable cathode and screen. Fig. 6 shows the results of both types of determinations, and also that over a wide range the magnification is quite accurately given by $v/(2u)$. It should be noted that the image position is independent of the difference of potential between the two cylinders.

The practical difficulty with this system lies in the fact that it is almost impossible to construct and mount the cylinders in such a way that the image will be perfectly in focus, and to construct the tube in such a manner that its mechanical dimensions can be changed after the tube has been exhausted and sealed is rather impracticable, though not impossible.

In order to focus the system electrically, it is necessary to change the curvature of the equipotential surfaces near the "lens" without so changing the field close to the cathode that the distortion of the image is increased. This could best be done by making the cathode-to-lens cylinder of resistive material, so that a potential gradient could be established along it. Experimentally, it is found that if the cathode cylinder is subdivided into four or more rings, each at a progressively higher potential, the distortion of the image is no greater than for the mechanically focused tube. The magnification of this type of tube is also given by $v/(2u)$.

These two types of tubes will give a fairly satisfactory image if the percentage of the cathode area used is small. The image suffers, however, from two defects: first, from pin-cushion distortion; and second, from the fact that a truly sharp focus can only be had at one value of the radius on the screen. Fig. 7 (Plate 1) is a photograph of the image obtained on the fluorescent screen when the entire cathode is illuminated with a rectangular grid. A study of the pattern shows that the image field is curved in such a way as to be convex from the lens side. Without changing the actual lens system, we have two means for correcting the above-mentioned distortion: first, by producing a radial gradient over the cathode; and second, by properly shaping the cathode surface.

The first method is not at present of much practical importance, but it is of interest theoretically. It can be applied by making the semi-transparent cathode film so that it is resistive, and then passing a current radially outward from the centre. The resistance of the film is not, however, uniform, but is lowest at the centre, increasing proportionally to the square of the radius towards the rim. By making the centre positive and correctly proportioning the resistance, both pin-cushion and de-focus effects can be corrected. Since electrical contact must be made to the centre of the film, however,

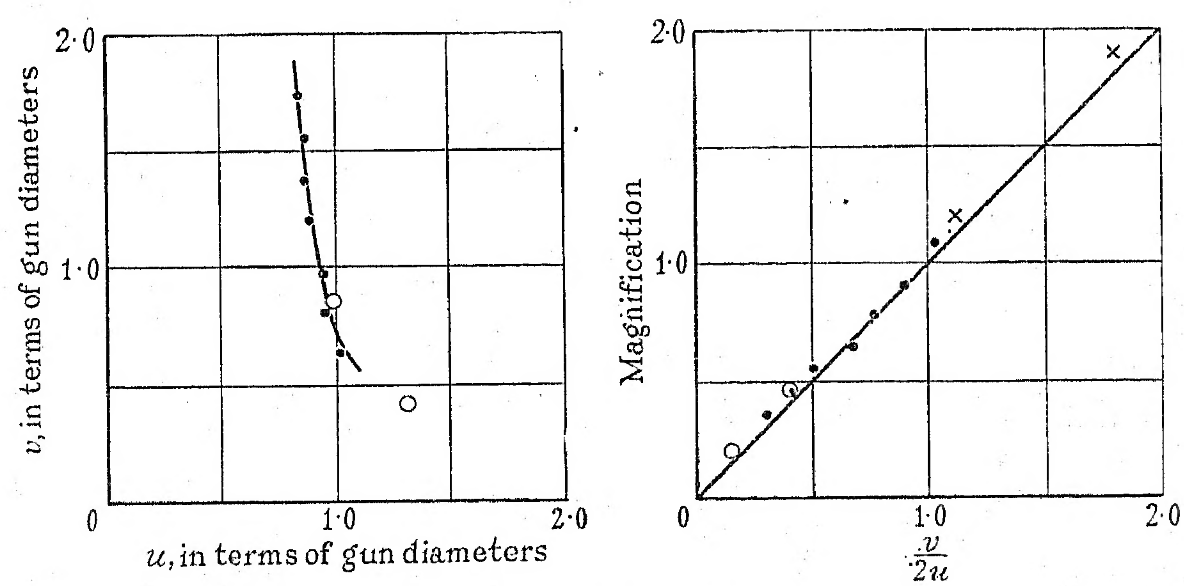

Fig. 6

● Fixed focus } (experimental values).
× Variable focus }
○ Fixed focus (calculated values).

it is impossible to avoid a blemish at the centre of the image.

It is interesting to note that these cathodes can be made self-correcting for a given value of light by making the film of uniform high resistance. When this is done, the photoelectric current produces a gradient over the cathode just as did the radial current in the previous case. The disadvantage of this solution to the problem is that the correction is complete for one value of light only and, furthermore, the illumination over the optical image must be fairly uniform.

The second method, that of shaping the cathode, is much more practicable and can be made to yield an excellent image over the entire cathode area. In making this correction, the first thought might be that the cathode should be convex towards the lens in order to bring the centre of the object closer to the lens, thereby correcting both the pin-cushion distortion and curvature of the field. The primary cause of this distortion, however, is the change of the radii of curvature of the equipotential surfaces with distance away from the axis, near the plane cathode. Introducing a convex surface only accentuates this effect. If, however, the cathode

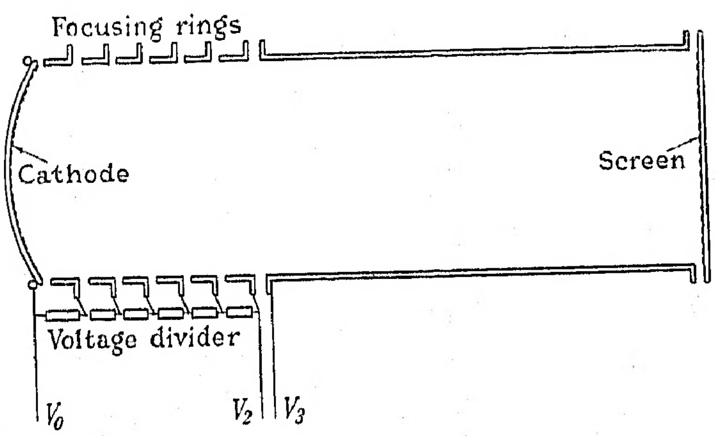

Fig. 8.—Image tube: fixed magnification

surface is concave towards the lens, the shape of the equipotential surfaces may be so adjusted that a perfect image can be obtained. It is found experimentally that if the cathode is spherical and of radius equal to the lens distance u, very satisfactory results are obtained.

Fig. 8 shows diagrammatically the construction of an image tube with curved cathode and focusing rings. It should be mentioned here that it is unnecessary to bring out separate leads for each of the rings making up the focusing cylinders. Instead, the potential divider supplying the voltage to these rings can be mounted within the tube itself. A photograph of the same grid pattern as that used in Fig. 7 is shown in Fig. 9 (Plate 1). It will be seen that the image is uniformly sharp and that the pin-cushion distortion is negligible.

So far, I have spoken only of lens systems using no apertures. While the presence of apertures somewhat complicates our picture of the electrostatic field making up the electron lens, certain general features remain the same. The field is cylindrically symmetrical as before, the lens system as a whole is positive and capable of producing a real image, and, finally, the same type of image distortion occurs as in the tubes described above—unless a corrected cathode is used.

Three arrangements of apertures applied to the type of tube just described are shown in Fig. 10. The first case is that of two symmetrical apertures. With this system the magnification will be found to be $v/(2u)$, as before, but the focal length for a given ratio V_1/V_2 is shorter. This means, in a practical case, that the voltage-difference between the anode cylinder and the final focusing ring can be made less, with a consequent

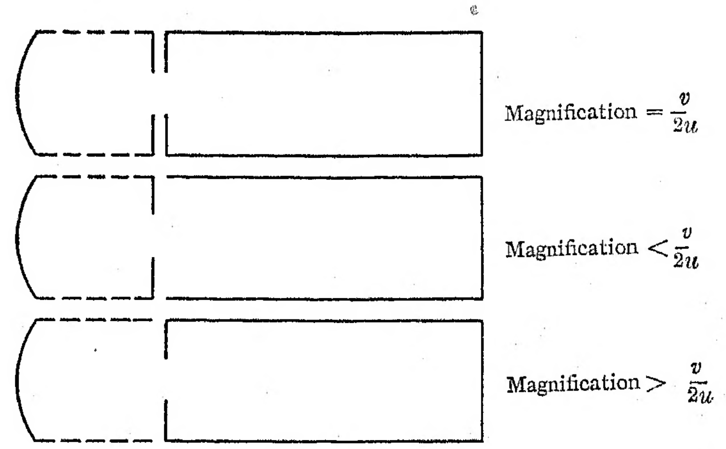

Fig. 10.—Arrangement of apertures in image tube.

simplification of the insulation problem and decrease in the danger of cold-cathode discharge.

Where the apertures are not symmetrical the magnification is no longer given by $v/(2u)$. If the aperture on the anode cylinder is smaller than the aperture on the final focusing ring, the magnification is greater than that given by the above relation, while if the anode aperture is the larger the magnification is less. The use of unsymmetrical apertures allows a wide variation in magnification in tubes which otherwise have identical construction.

The final case to be considered is that shown in Fig. 11. This type of lens system has an aperture placed midway between the anode cylinder and the final focusing ring whose potential V_3 can be varied. It should be noted

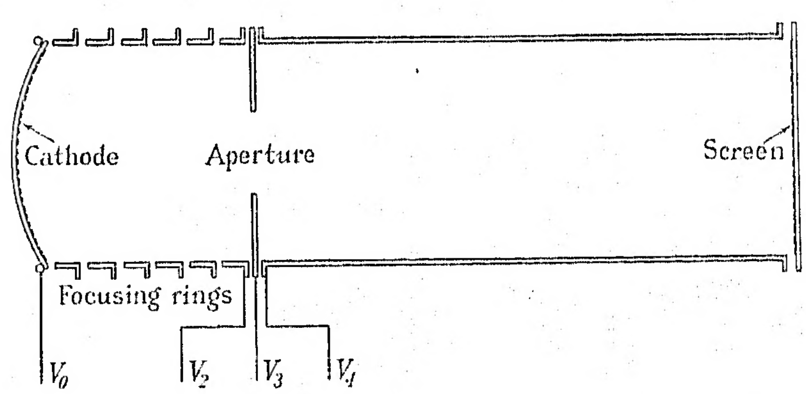

Fig. 11.—Image tube: variable magnification.

that when the aperture potential V_3 equals the anode voltage, the conditions are similar to those of the case just described where the aperture on the anode cylinder is smaller than that on the focusing ring, and the magnification will be greater than $v/(2u)$. Likewise, when V_3 is made equal to the ring potential, the magnification is a minimum. For intermediate values of V_3 the magnification lies in between these extremes.

The pin-cushion distortion is a maximum when V_3 is equal to ring potential or less, but decreases rapidly to a constant value as V_3 is increased. Over nearly the entire range of magnification, a curved cathode will

correct this distortion fairly satisfactorily. With this arrangement it is possible to construct a tube which gives a very satisfactory image and whose magnification can be controlled electrically.

An interesting use to which this type of tube may be put is exemplified in the electron telescope. A large-aperture lens is mounted so as to form an image of the scene towards which the telescope is pointed, on an infra-red sensitive cathode of an image tube. The electron picture falling on the fluorescent screen renders visible the infra-red image. Such a device can be used to test haze and smoke penetration by infra-red rays, for signalling, etc.

Another use is in connection with infra-red microscopy. Fig. 12 (Plate 1) shows an image tube and microscope arranged for infra-red work. The visible image on the fluorescent screen of a micro-specimen is shown in Fig. 13 (Plate 2). Black gum was used in this case as the packing material.

The next two pictures (Figs. 14 and 15, Plate 2) were made by photographing the fluorescent screen while an infra-red picture was projected on the cathode. They illustrate fairly well the resolution and fidelity of the image obtainable. Fig. 16 (Plate 2) is a photograph of the electron telescope, and Fig. 17 (Plate 2) a photograph of an image tube with 9-in. screen.

PART II

SECONDARY-EMISSION MULTIPLIERS AND ELECTRON OPTICS

Leaving, now, electron optics as applied to image formation, I propose to discuss another field in which its application is extremely important. This is the field of secondary-emission multipliers. In this section, emphasis will be placed on the general design and operation of these multipliers rather than on electron optics; but the important role that this science plays will be very apparent.

It has been known for many years that when certain surfaces are bombarded with cathode rays they emit electrons. This effect, known as secondary emission, has, from an early date, been extensively studied by a large number of workers such as Lenard, Hull, and Von Bayer. The study of this phenomenon revealed that the number of electrons emitted is proportional to the bombarding current, the factor of proportionality ranging from a mere fraction to 10 times as many secondary as primary electrons. The value of this ratio depends upon the surface used and on the velocity of the bombarding electrons.

Although these facts have been known for a long time, the effect had not until recently found any useful application, except in the case of the dynatron invented by Dr. Hull. In fact, secondary emission had chiefly been looked upon as a serious obstacle in the design of thermionic vacuum tubes, and much research had been carried on with a view to suppressing and reducing it. During the past 15 years it became recognized that secondary emission could be used as a means of amplifying a small initial electron current, and a number of workers began investigating in this field. Patents for methods of applying this idea were filed as early as 1919 by Slepian,* and later by such workers as Jarvis and Blair,* Iams and Salzberg,† Farnsworth, and others.

* Patent No. 1450265, 3rd April, 1923 (1919).

The general method involved is to allow the initial electron stream to impinge upon a target which has been sensitized for secondary emission. The secondary electrons from this target are directed on to a second target, producing still further electrons, the multiplication being repeated as many times as is desired. Reference to Fig. 18 will make this process clear. In this figure, electrodes A, B, C, etc., represent a number of plane targets having a high secondary-emission ratio. These electrodes are connected to successively higher positive potentials. The stream of electrons to be multiplied is directed against A. This target gives rise to secondary electrons which go to target B, in turn giving rise to secondary electrons which are directed against C. After this process has been repeated a sufficient number of times to give the desired overall multiplication, the electrons from the final target are collected on collector O. If s be the number of secondary electrons per primary for each stage and n the total number of stages, then the initial current I_0 will be multiplied up to an output current $I_0 s^n$. Clearly, the overall gain will be s^n times. It will be seen that the overall gain becomes very large indeed as the number of stages is increased.

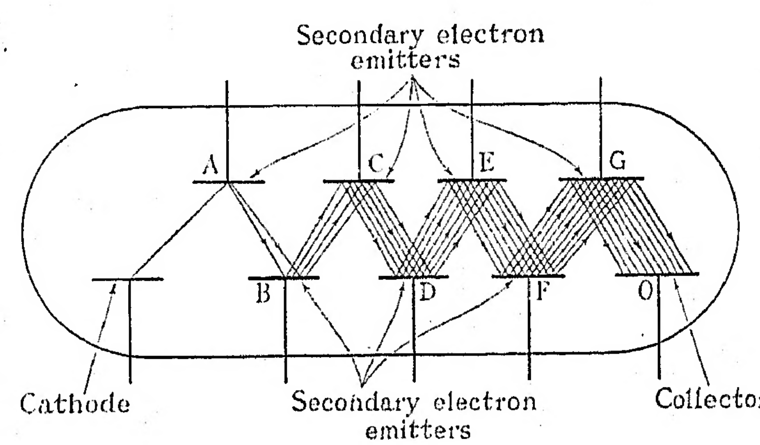

Fig. 18.—Simplified secondary-emission multiplier.

A second class of multipliers has been described by P. T. Farnsworth‡ in which the electrons are made to go back and forth between a single pair of targets, getting their energy from a high-frequency electric field. Of these two classes of multipliers, only the static type using successive targets, wherein the number of impacts can be rigorously controlled and the stability is consequently very great, will be discussed in this paper.

The problem of making a multiplier to give high gain is not, however, so simple as it might seem at first sight. A simplified multiplier constructed in accordance with the diagram (Fig. 18) would be almost completely inoperative, for the reason that practically all the electrons leaving any target would not go to the following one, but would merely go down the length of the tube and be collected at the final collector with almost no multiplication. In order to construct a successful multiplier, not only must the target have a high secondary-emission ratio, but also means must be provided to focus the electrons on to each target, and to draw away secondary electrons

* Patent No. 1903569, 11th April, 1933 (1926).
† *Proceedings of the Institute of Radio Engineers*, 1935, vol. 23, p. 55.
‡ "Television by Electron Image Scanning," *Journal of the Franklin Institute*, 1934, vol. 218, p. 411.

from one target preparatory to focusing them on to the next succeeding target.

Before taking up the methods of electron focusing employed in specific multipliers, I shall discuss certain general aspects of fixed-field multipliers.

(1) General Considerations

(a) Secondary Emission.

Since the successful operation of these multipliers depends upon a high secondary emission from the targets, it is of prime importance to discover the most suitable surfaces to use. In our search for good emitters, very little aid can be obtained from the theoretical physicist. The most complete treatment of the theoretical aspect of secondary emission in the light of quantum mechanics was published by H. Fröhlich* in 1932.

In this discussion he calculates the probability of the transfer of energy between an incoming primary electron and a conduction electron moving in the periodic potential field of the metal, where the exchange is such as to give the conduction electron sufficient momentum

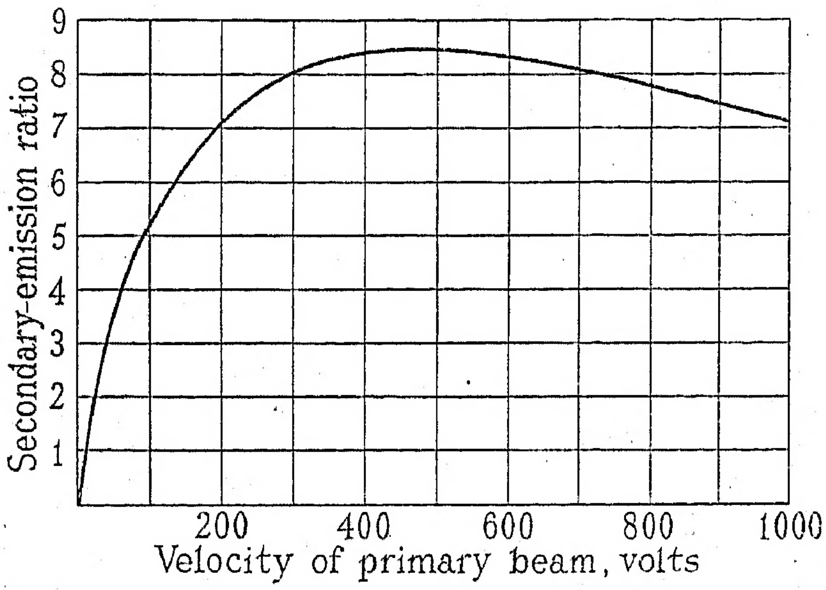

Fig. 19.—Ratio of secondary-emission current to primary current for Cs-CsO-Ag surface.

to escape from the metal. On this basis, he concludes that metals with a crystal structure having a large lattice spacing and with a low work function should be the best secondary emitters. This treatment, however, applies only to simple metal surfaces.

Experimentally, it has been found that the emission ratio from simple metal surfaces is invariably below that obtained from composite surfaces, just as with photoelectric emission. Since the theoretical knowledge of secondary emission does not extend to these composite surfaces, it is necessary to go ahead on a more or less empirical basis, keeping in mind that, other things being equal, a surface of low work function is the most likely to be a good emitter. A large number of low work-function surfaces were therefore studied having as a base metal Ag, Be, Ta, Ni, Al, Zr, Ca, W, etc., and Na, K, Rb, and Cs as a surface layer. Of these, the most satisfactory to date have been oxidized Ag, Be, or Zr, with a surface layer of caesium. These surfaces have a maximum ratio of from 8 to 10, occurring at a bombarding velocity of from 400 to 600 volts.

* *Annalen der Physik*, 1932, vol. 13, p. 229.

A curve showing the secondary-emission ratio of a Cs-CsO-Ag surface for various bombarding voltages is given in Fig. 19. This is typical of the surfaces frequently used in the multipliers to be described later. The method of preparation of this surface is very similar to that used in the preparation of the photoelectric cathode for a high-vacuum caesium photocell.

(b) Multiplier Efficiency.

There are two ways of considering the efficiency of a multiplier. The first is to measure the efficiency of secondary emission as a source of electrons, in terms of amperes per watt supplied; while the second considers gain obtainable for a given overall voltage as a function of the number of stages and the voltage per stage. The second of these two considerations is more important from a practical standpoint, but both are worthy of some discussion.

From Fig. 19 the curve of the emission plotted against bombarding voltage, as shown in Fig. 20, can readily be

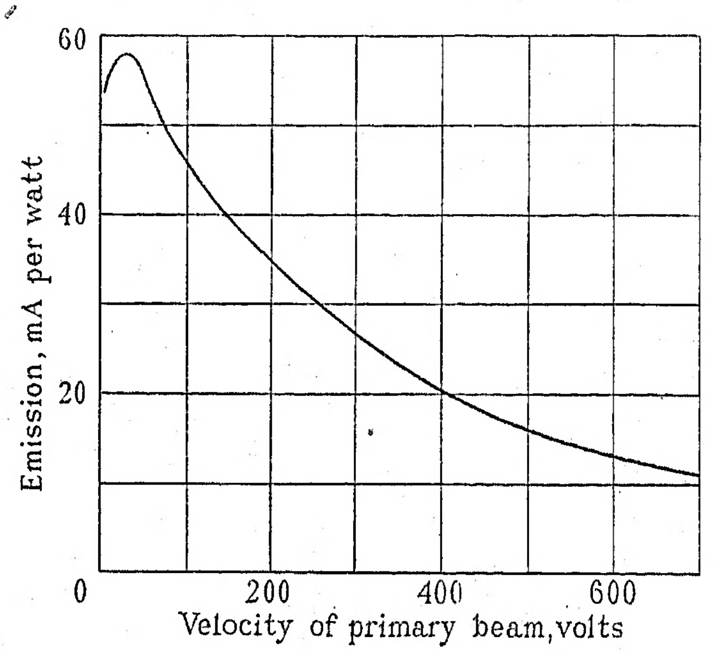

Fig. 20.—Curve of current per watt for secondary emission of Cs-CsO-Ag.

calculated. This curve shows that the maximum emission, which occurs at about 30 volts, is 60 mA per watt (a gain of 0·06 per volt), dropping to 45 mA per watt at 100 volts, and 17 mA per watt at 500 volts. For comparison, it may be mentioned that a good thoriated-tungsten thermonic cathode will deliver 50 to 75 mA per watt, while an oxide-coated cathode may give as much as 100 mA per watt. Thus, while secondary emission is not the most efficient way of obtaining an electron current, it compares rather favourably with other methods.

The question of maximum overall gain will be made clearer by reference to Fig. 21. This family of curves shows the gain that can be obtained from multipliers with various numbers of stages, plotted against voltage. These curves show that the most efficient multiplier is one operated with 40–50 volts per stage. Run in this way, such a multiplier gives very high gains. For example, a 10-stage multiplier at 500 volts will have a gain of 30 000, while a 15-stage multiplier at 800 volts will multiply the initial current 10 million times. It should be noted that the curves in Fig. 21, and the overall

voltages given, do not include the voltage between the collector and the last target, as this will depend upon the use to which the tube is to be applied.

(c) Noise in Multiplier Output.

Turning now to the question of noise, which is the limiting factor in the amplification of these multipliers, we have to consider chiefly the statistical fluctuation of the useful electron current through the tube. From theoretical considerations verified by experiments, it can be stated that the signal/noise ratio obtainable from multipliers is practically that determined by the shot effect in the original photoelectric current.*

There are two other factors which limit the sensitivity of these multipliers; they are (i) thermionic emission from the secondary emission targets, and (ii) noise due to the positive-ion emission. These two factors, while troublesome, can be overcome if proper precautions are taken. Therefore, it may be said that the shot noise of electron emission sets the fundamental limit to the sensitivity of the secondary-emission multiplier. For low light intensities the gain in signal/noise ratio is from 60 to 200 times when compared with an ordinary amplifier under usual operating conditions.

(d) Frequency Response.

The frequency response of the secondary-emission multiplier is flat over a very wide range of frequencies. Between the upper limit and a direct-current signal, the frequency response is essentially uniform.

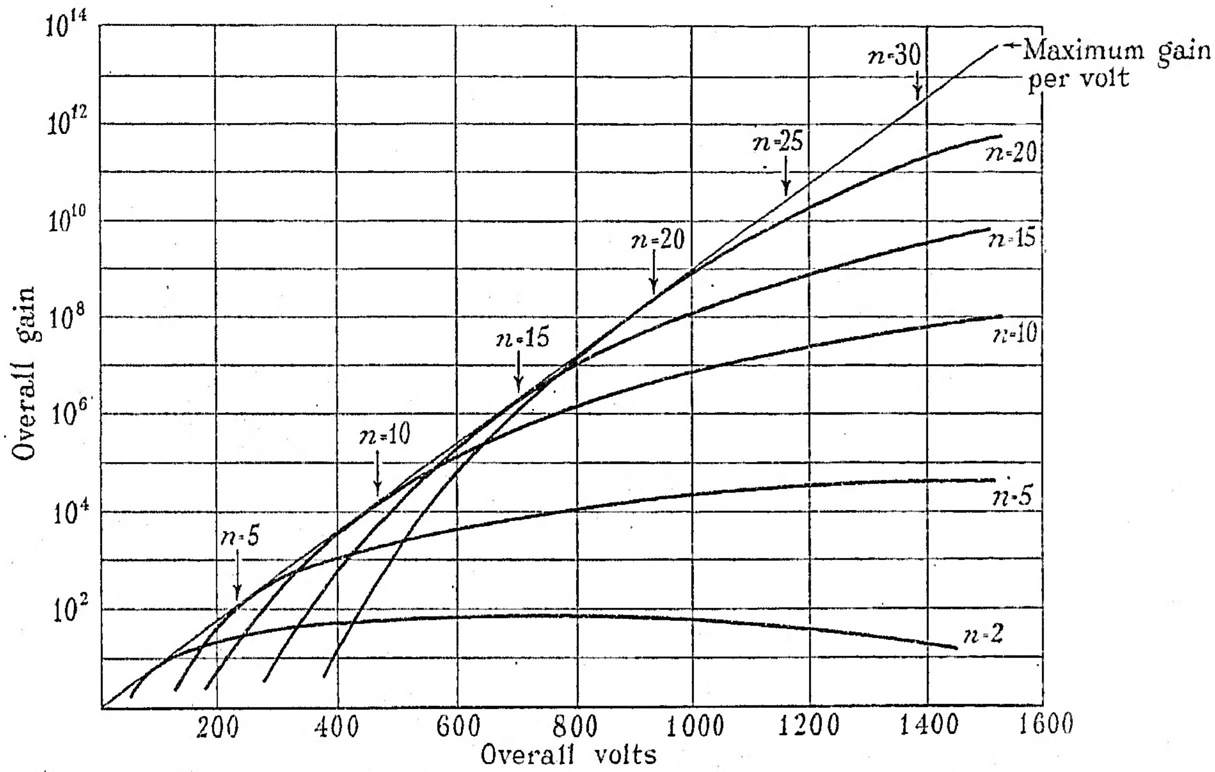

Fig. 21.—Gain obtainable with secondary-emission multiplier.

(2) Magnetic Secondary-Emission Multiplier

(a) Theory of Operation.

We shall now consider an electron multiplier with crossed magnetic and electrostatic fields, designed to separate and focus the secondary electrons from one target to the next. This configuration of fields and electrodes was first suggested by Slepian in 1919, for use as a high-current cathode.

The general arrangement of a multiplier based on this principle is shown in Fig. 22. It consists of two rows of electrodes, the bottom row being secondary emitters, while the upper row serves solely to maintain a transverse electrostatic field between the two sets of elements. Each target in the bottom row is made positive with respect to the preceding one so that it will produce secondary electrons when struck by electrons originating

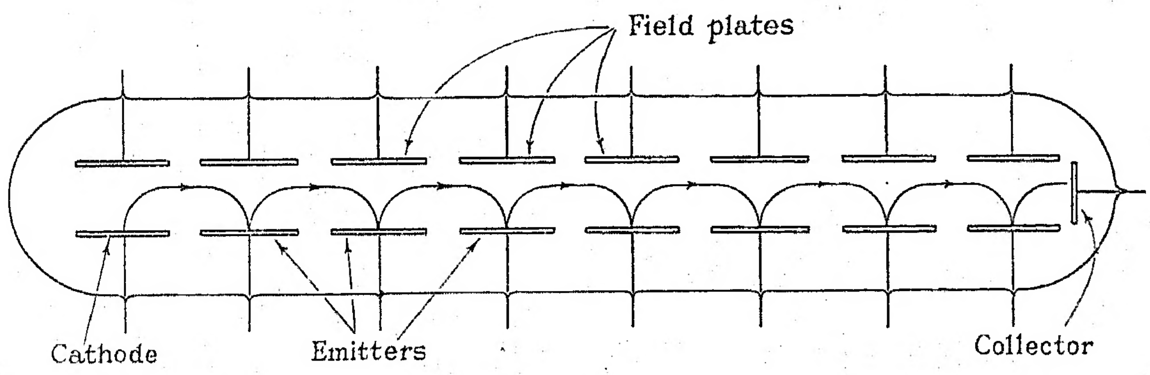

Fig. 22.—Magnetic secondary-emission multiplier.

* A. W. HULL and N. H. WILLIAMS: *Physical Review*, 1925, vol. 25, p. 147; F. M. PENNING and A. A. KRUITHOF: *Physica*, 1935, vol. 2, p. 793; L. J. RAYNER: *Physics*, 1935, vol. 6.

from the latter. A magnetic field is established in the tube at right angles to its axis and to the field between the two rows of plates. Electrons leaving any of the lower plates are bent by the combined fields in such a way that they strike the next target, giving rise to

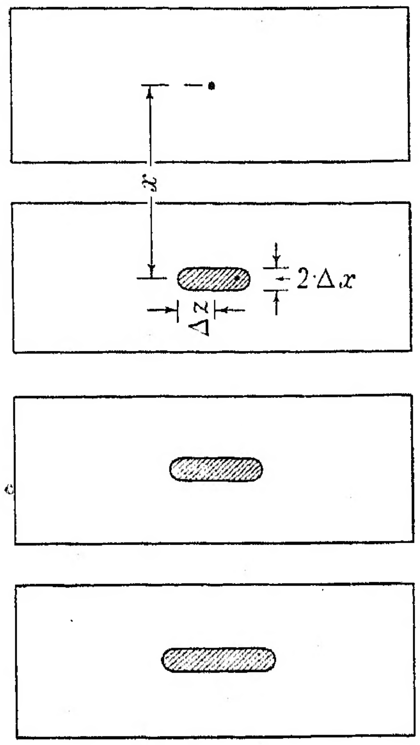

Fig. 23

secondary electrons, which are in turn deflected on to another target, and so on, through the tube.

Under the influence of these two fields, electrons are separated from the primary and are focused on succeeding targets. This focusing can be compared with that of a cylindrical optical system, in that the focusing can be almost perfect in one direction but very ineffective in the opposite direction. This means that electrons leaving from a point on the cathode are spread into an elliptical spot on the first target. This spot, in turn, is spread into a larger ellipse on the second target, the size of the spot increasing as the electrons progress down the tube. This effect is illustrated schematically in Fig. 23.

Eventually, the spot becomes so large that some of the electrons miss the target entirely, and there is a dropping-off of the efficiency of the subsequent stages. The transverse spreading is such that there would be a serious loss after a comparatively few stages unless special precautions were taken to prevent this type of defocusing.

(b) Design and Construction of Magnetic Multiplier.

A schematic diagram of the actual application of the principles described above to a multiplier photocell, is shown in Fig. 24. Photo-electrons are focused upon a target 1a. Secondary electrons from this electrode will be focused on target 2a, giving rise to further electrons, and so on, for as many stages as is desired.

The plates are mounted in the tube in such a way that the upper and lower plates are as close together as is possible in order to make the potential gradient large and thus increase the current that can be drawn away from a target before space-charge limitations occur. This minimum spacing is half the distance between centres of successive targets. With this construction it is found that the current which can be drawn from the tube is limited only by the power that can be dissipated from the final stages in overcoming the heat generated due to electron impacts.

In order to limit the sideway spreading, the electrodes are mounted on vertical strips of mica. Charges which accumulate on these vertical walls so alter the field as to introduce an additional lens action which limits sideway spreading. With this arrangement the limit to the number of stages which may be used is set by the axial defocusing, but this defocusing is so small as to permit the use of a great many stages. The upper limit to the number of stages has not been determined experimentally, although multipliers employing as many as 12 stages without a decrease in gain per stage have been constructed.

When multipliers are operated at high gains into high-impedance loads, some difficulties are encountered due to oscillation. This can be eliminated by surrounding the collector electrode with a shield grid, as shown in Fig. 24. The grid serves as an electrostatic shield and prevents changes of collector potential from reacting back upon earlier stages. It also results in the output characteristic

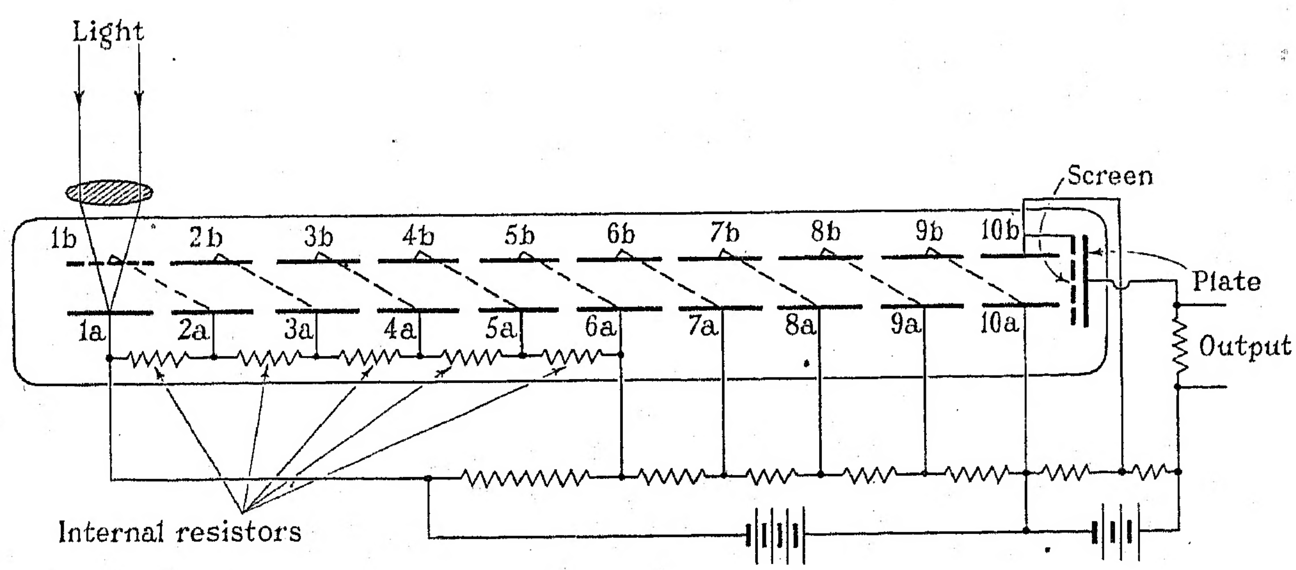

Fig. 24

Fig. 2

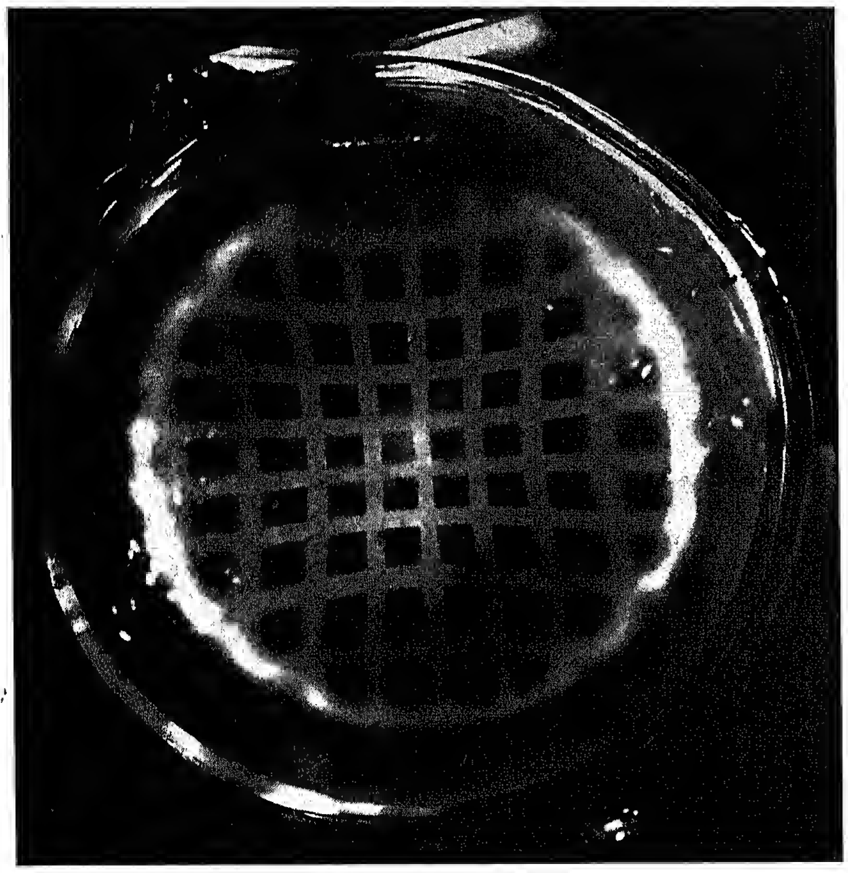

Fig. 7

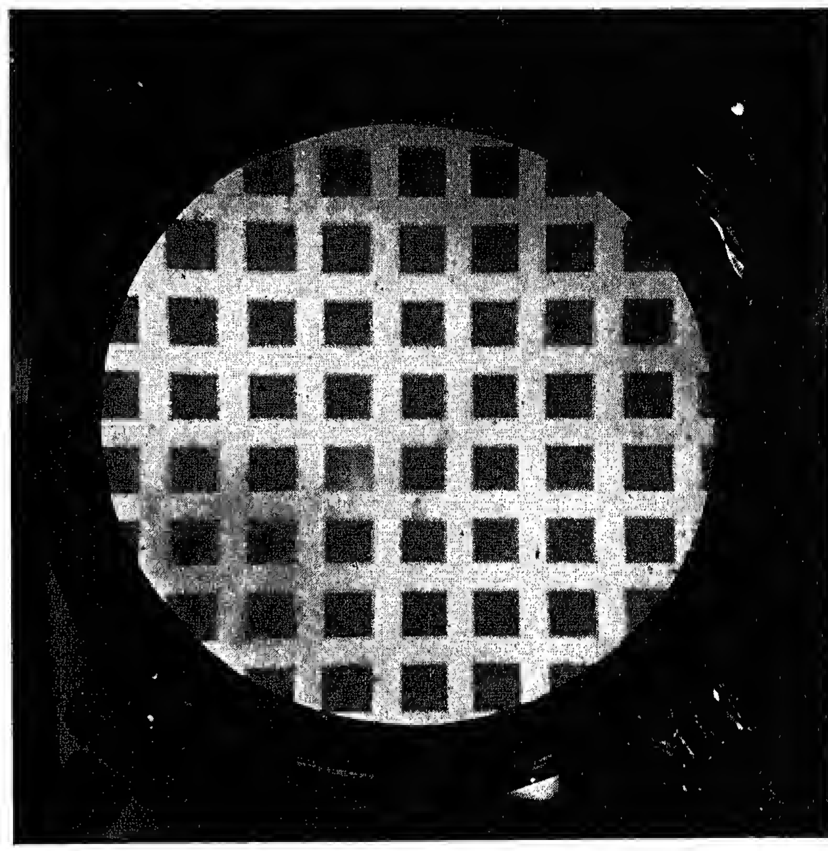

Fig. 9

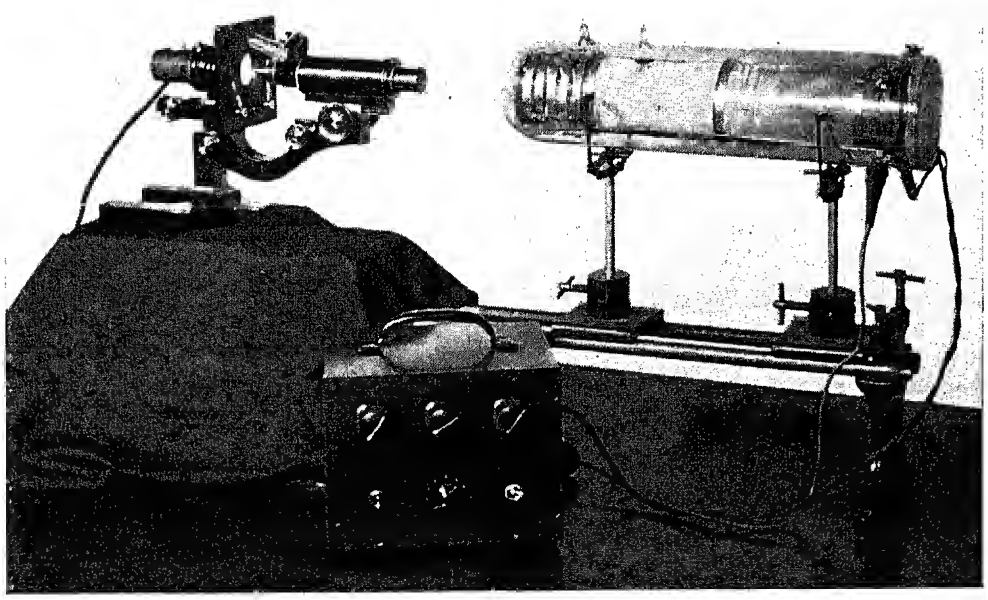

Fig. 12

Plate 2

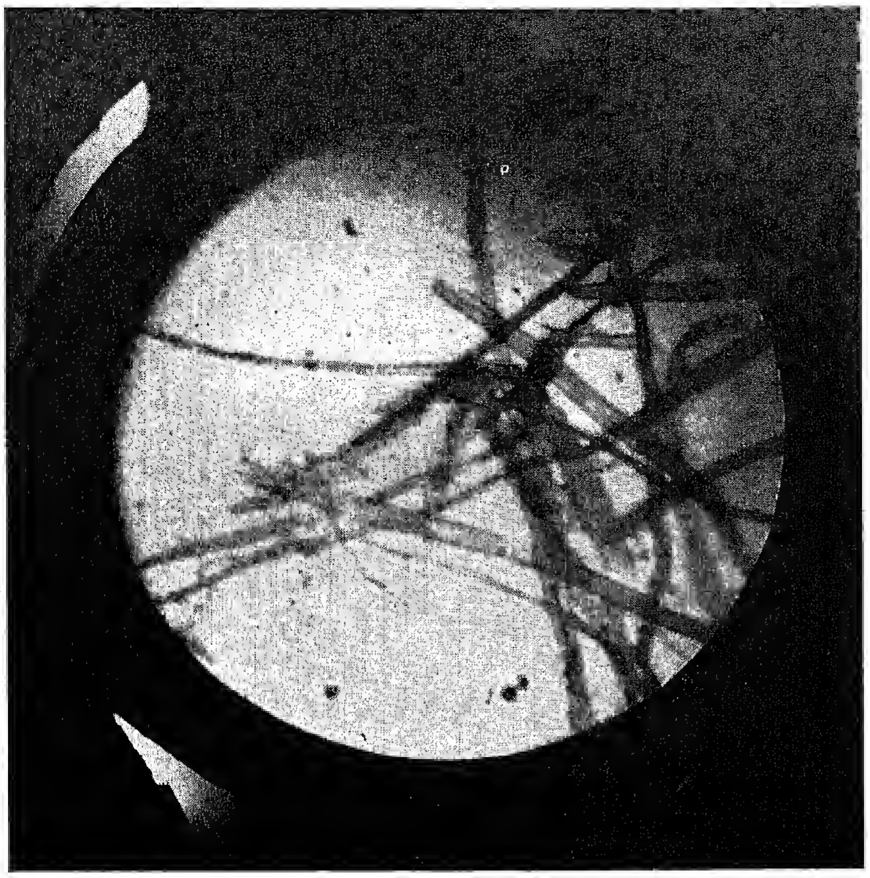

Fig. 13

Fig. 14

Fig. 15

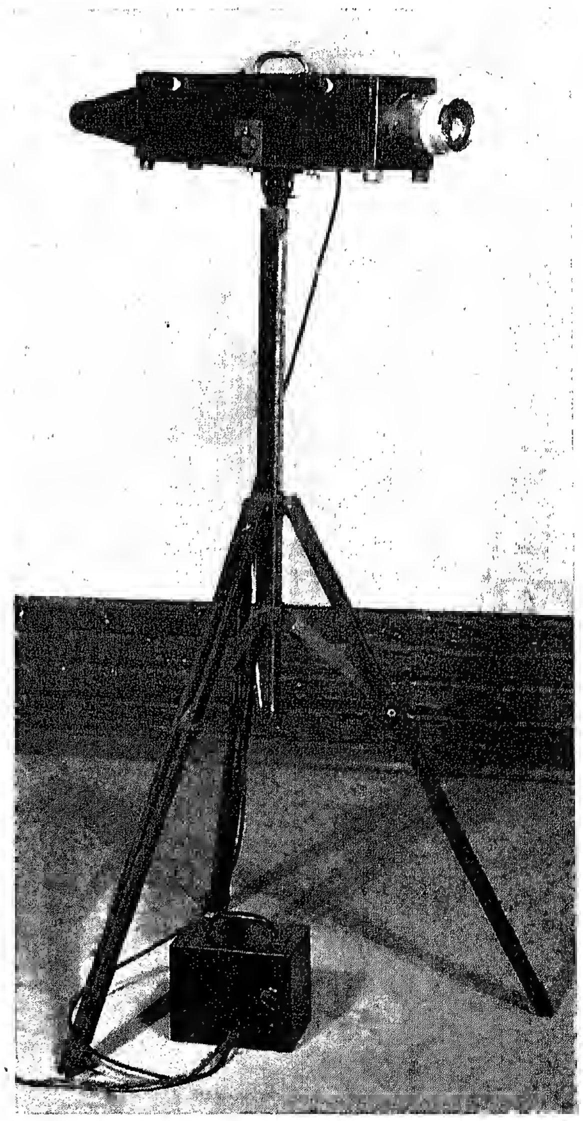

Fig. 16

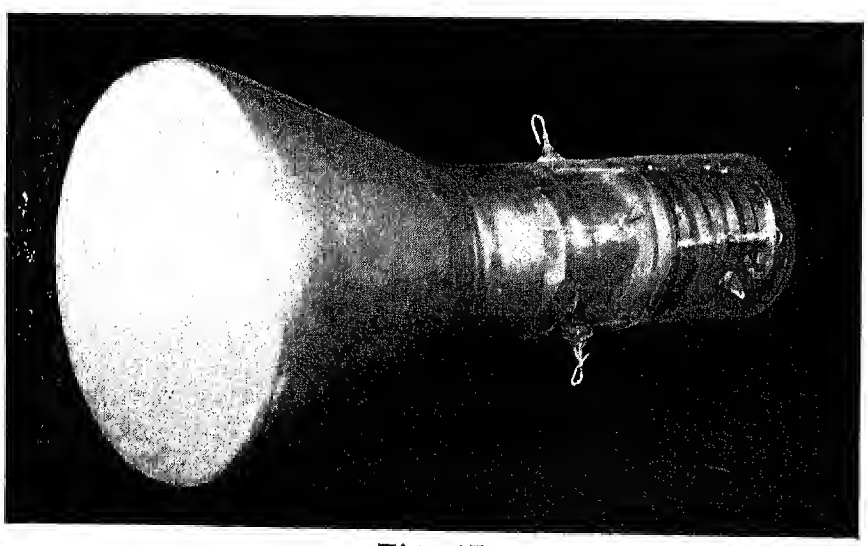

Fig. 17

Plate 3

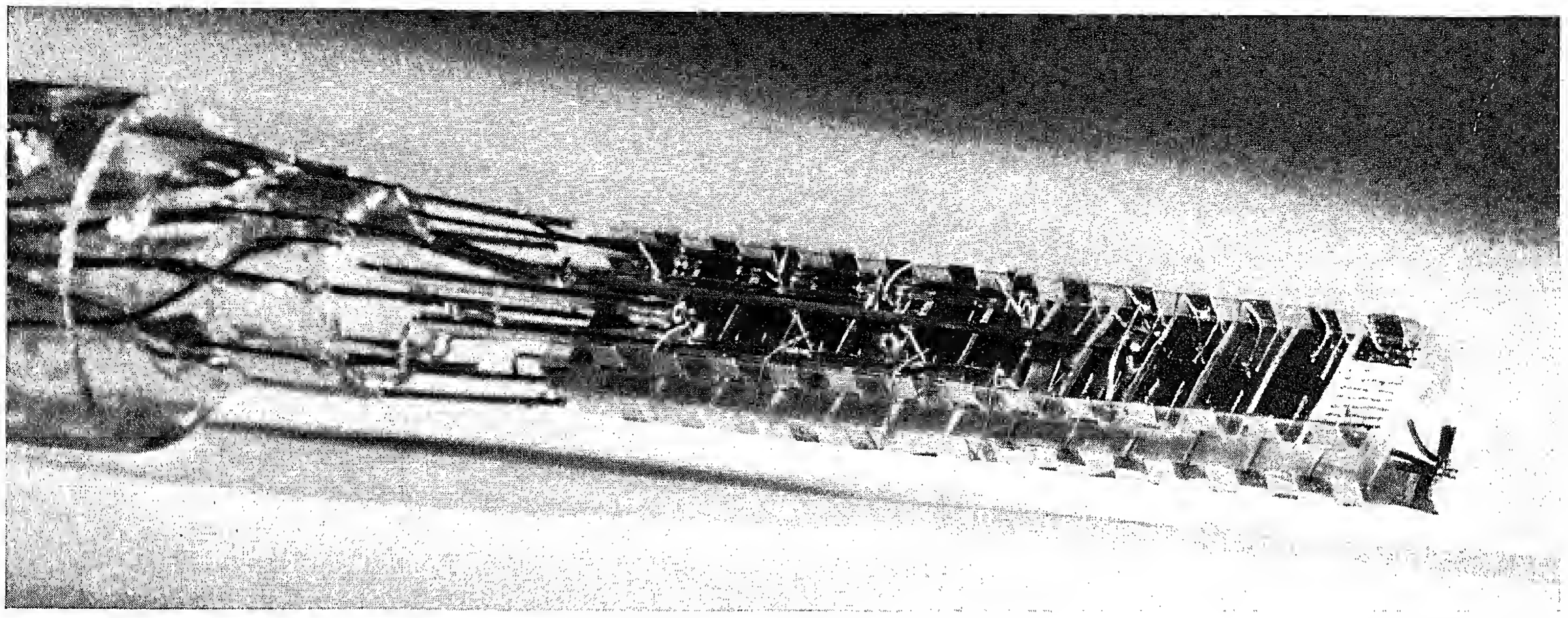

Fig. 25

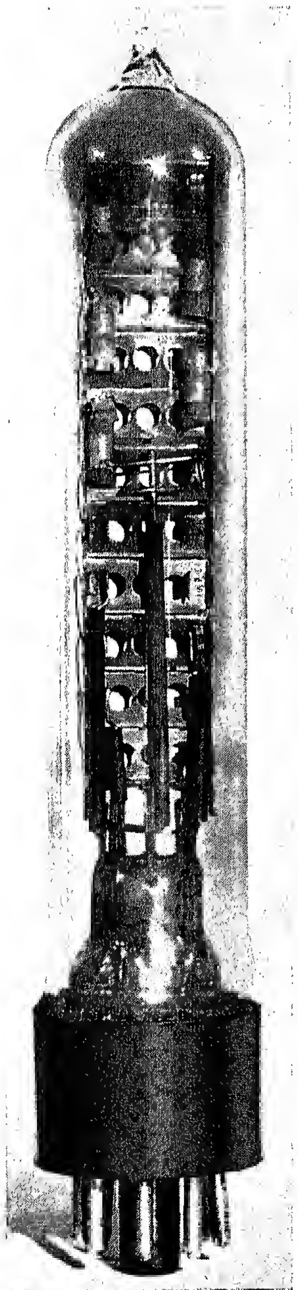

Fig. 31

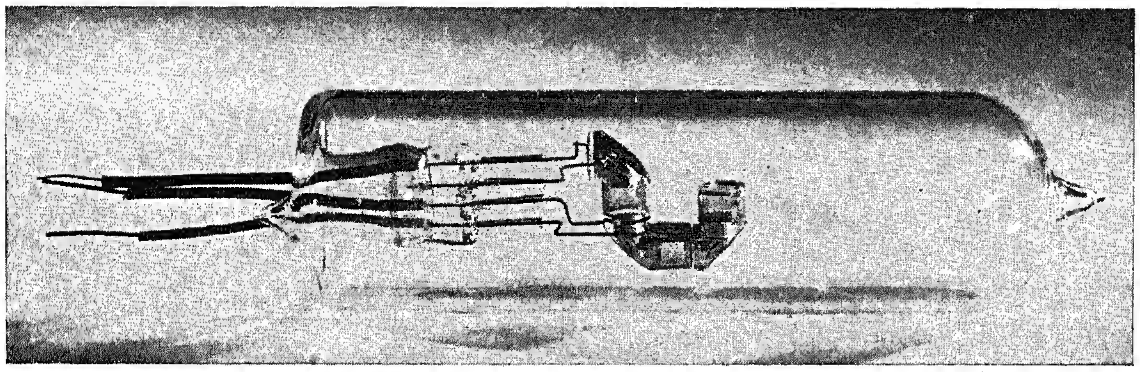

Fig. 29

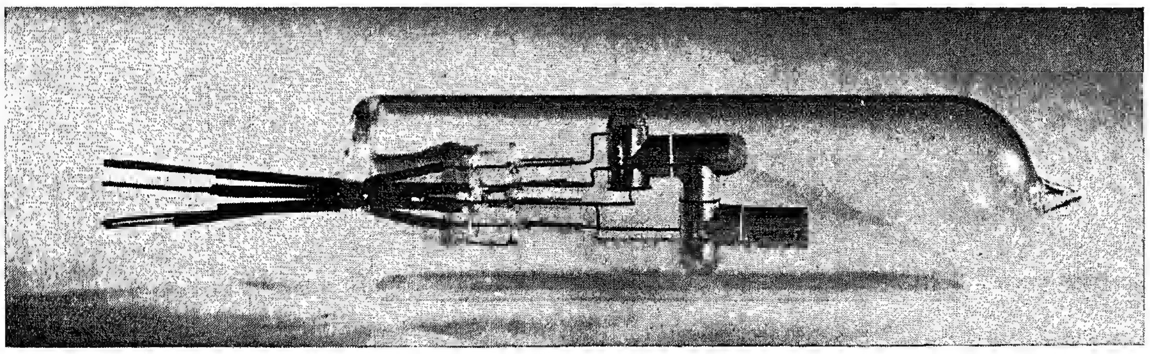

Fig. 30

Fig. 32

being altered from that of a triode to that of a conventional screen-grid tetrode.

For operation of the device, it is necessary that the upper electrodes be at a fixed positive potential with respect to the corresponding lower electrode, and that the voltage-steps between adjacent electrodes be equal. In order to decrease the number of leads required, it has been found advantageous to connect upper electrodes to lower targets farther down the tube. Satisfactory results have been attained with each upper electrode connected to the next succeeding lower target.

Since the first few targets draw almost no current, their potential can be very satisfactorily supplied from a voltage-divider or bleeder. In order to decrease further the number of leads in a multiplier employing many stages, it has been found practicable to incorporate the bleeder for the initial stages inside the tube.

It has also been found possible to operate the device with alternating voltages on the electrodes. The operation will, of course, occur over only a portion of each cycle. The frequency of the applied alternating current must exceed the highest frequency which the multiplier is to transmit.

As a means of supplying the requisite magnetic field, permanent magnets have been found to be very satisfactory. These are superior to electromagnets from the standpoint of size and also in view of the fact that no external power is required.

An enlarged photograph of the internal structure of a 12-stage multiplier in which the voltage divider for the first five stages is incorporated in the tube, is shown in Fig. 25 (Plate 3).

(3) Electrostatic Multiplier

Where the application of a secondary-emission multiplier does not permit the use of a magnetic field, it is necessary to use a multiplier in which the electrons are focused by electrostatic fields alone.

The problems involved in designing the focusing system for such a multiplier are similar to many of those met with in an electron microscope. It can be shown

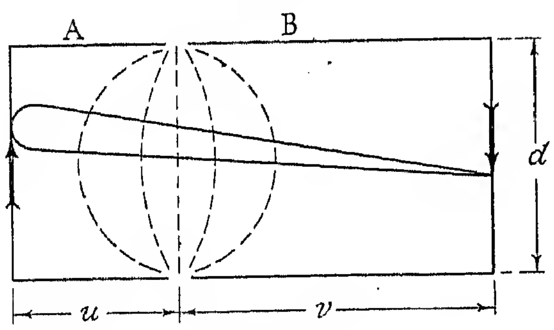

Fig. 26

$u \simeq \frac{2}{3}d$
$v \simeq \frac{4}{3}d$
Magnification = 1

that in general a radially symmetrical electrostatic field will have the properties of a lens over portions of the field near the axis of symmetry. The radial distance from the axis over which this condition applies will depend upon the field configuration. The focusing system of the electrostatic multiplier is based on the field between two coaxial cylinders. Since it is desirable to have a minimum of separate voltages to operate the tube, one cylinder is made part of one target while the other is connected to the next succeeding emitter. The configuration is made such that electrons from an area in the centre of the first target will come to a focus at the

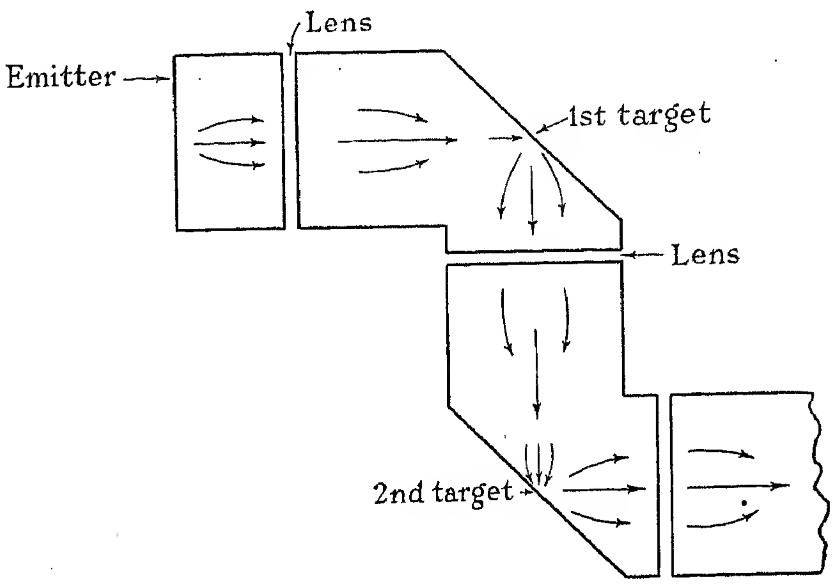

Fig. 27.—" L " type multiplier.

centre of the next, and that the magnification of the electron image formed will be unity.

This electron " optical " system is similar to those described earlier in this paper and will be made clear by reference to Fig. 26. In this diagram the lens is formed between the cylinders A and B, A being at earth potential, while B is at the potential V. The electrons are emitted from the cathode in A with a very low velocity, are deflected by the " lens " formed between the two cylinders, and are focused on to the screen or electrode in B, striking it with a velocity of V electron volts.

The application of this optical system leads to the so-called " L " type multiplier whose construction is shown in Fig. 27. This multiplier is quite satisfactory from

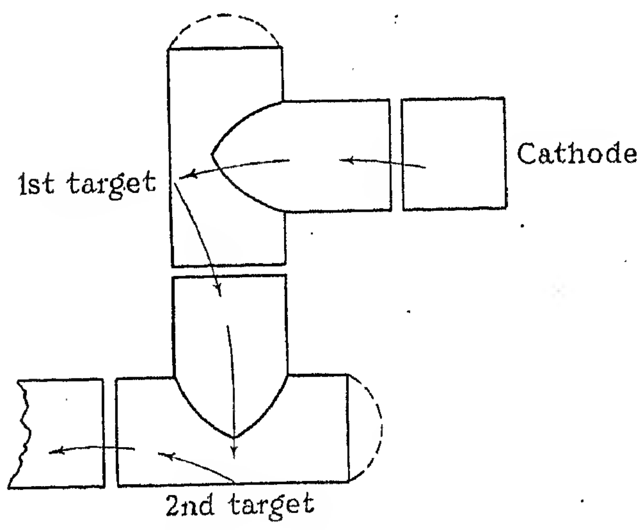

Fig. 28.—" T " type multiplier.

the standpoint of focus, but the field at each target drawing away the secondary electrons is rather weak and the multiplier becomes space-charge-limited at rather small current values. Further, the emitting spot on the initial cathode must be small if accurate focus is to be maintained.

A second type of multiplier has been designed which does not depend upon so sharp a focus and which has a

higher collecting field at the targets. This is the "T" type multiplier which is shown in Fig. 28. This multiplier is built so that the cylindrical exits from the targets are as short as possible and yet long enough to ensure that electrons entering through the stem of the "T" will not be deflected sufficiently by the field from the succeeding electrode to miss the target. The targets are formed by sensitizing the whole inside of the cylindrical cross-arm of the "T." Even with this arrangement, where currents of the order of 1 milliampere are to be used it is necessary to operate the multiplier at a fairly high voltage per stage, i.e. 200–400 volts, if space-charge effects are to be avoided. Figs. 29 and 30 (Plate 3) show multiplier photocells of the "L" and "T" types.

(4) Applications

The most obvious application of these multipliers is as photoelectric amplifiers. This use is very much simplified in view of the similarity between the photoelectric and secondary emissive surfaces. The most convenient type of multiplier to use for this purpose is the type combining electrostatic and magnetic fields, because of the excellent focusing characteristics and the high current output obtainable. A tube of this type having a gain of several millions or an output of 10 or more amperes per lumen is but little larger than an ordinary receiving tube. A voltage of about 1 500 volts is required to operate such a tube, and since the current consumed is small it may be supplied from a small socket power unit.

Since it serves to replace not only a photocell but also its accompanying amplifier, there is obviously a great gain in simplicity and a saving in bulk. In addition, these multipliers are very stable, insensitive to external interference, and have an excellent frequency characteristic. An even more important factor is that the noise output is determined by the shot noise of the photoelectric effect, and therefore allows an increase of 60 to 100 times in signal/noise ratio under ordinary operating conditions for extremely low values of light. These facts combine to make this type of multiplier a very excellent means of converting a light signal into an electrical signal. The size of this tube may be compared with that of a conventional receiving tube by referring to Figs. 31 and 32 (Plate 3), which show to the same scale a 10-stage multiplier and an R.C.A. Type 59 tube respectively.

The applications of multiplier photocells are extensive, including in particular those of pick-up from sound film, facsimile, automatic door control, alarm systems, automatic sorting machines, etc.

Although at present the most important application of the secondary-emission multiplier is as a photocell, it has a number of other applications which may become increasingly important. In general, these multipliers can be used in connection with any device where the signal to be amplified is generated in the form of an electron current. This use includes types of electron commutator tubes such as are used for high-speed switching, secret sound systems, and frequency multipliers.

As a voltage-controlled amplifier, the device does not lend itself so readily. This is because, in general, to couple the input of a voltage-controlled amplifier to its external circuit it is necessary to use some form of coupling impedance, and this, as in the case of a conventional thermionic amplifier, will limit the signal/noise ratio obtainable. If the conventional type of thermionic cathode and control grid is used in connection with a multiplier, the problem of securing results superior to those obtainable with an ordinary vacuum tube presents considerable difficulties. There is the possibility of obtaining a higher percentage control per volt applied to the grid by deliberately throwing away a large fraction of the cathode current to gain this control, and then using a multiplier to bring the average current back to a higher level. This idea is still in its initial experimental stages, and it is too early yet to say what the outcome will be.

The secondary-emission multiplier is too new an instrument for it to be possible to foretell the full extent of its application; but even now it seems evident that it may become a serious rival to the thermionic amplifier in many of the fields which this has occupied alone for so long, and it may also open up new fields in the realm of the electronics of small currents.

In conclusion, I wish to express my thanks to Dr. G. A. Morton and Mr. L. Malter, who were associated with me in the work described in this lecture, and to acknowledge the valuable assistance rendered by the other members of the Electronic Research Laboratory of the R.C.A. Manufacturing Co., Inc., Camden, New Jersey.

FLUORESCENT SCREENS FOR CATHODE-RAY TUBES FOR TELEVISION AND OTHER PURPOSES

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SUMMARY

An account is given of the principal materials employed for the screens in cathode-ray tubes for television and other purposes.

The fluorescent and phosphorescent phenomena displayed by willemite, calcium tungstate and cadmium tungstate, zinc phosphate, and the various preparations of zinc sulphide and zinc-cadmium sulphide, are dealt with in detail. The method whereby the undesirable phosphorescence displayed by zinc sulphide and zinc-cadmium sulphide has been eliminated is explained.

Photometric measurements of the illumination of screens composed of a variety of materials under different conditions of excitation are given. A number of spectrograms are included of the fluorescent light emitted by these substances. The results show that:—

(1) Zinc sulphide and zinc-cadmium sulphide are the most suitable substances hitherto developed for fluorescent screens for cathode-ray tubes.

(2) A special zinc sulphide, giving approximately white fluorescence, has been obtained.

(3) A mixture of zinc sulphide and zinc-cadmium sulphide, giving a brilliant white fluorescence of high intensity, has been prepared.

(4) Phosphorescence, when not required, can be entirely eliminated.

(5) Zinc sulphide and zinc-cadmium sulphide giving prolonged phosphorescence can be produced, and these compounds find application for special purposes.

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(1) INTRODUCTION

Cathode-ray tubes have now assumed very great importance in many branches of electrical science. The fluorescent screen which is employed to render the effects of the electron stream visible is a most important portion of the apparatus. Upon its efficiency and characteristics the suitability of the cathode-ray tube for various purposes for which it is employed, will largely depend.

An account of the work on this subject which is being carried out in this country may therefore be of interest to members of the Institution, although the subject is primarily chemical in character.

(2) LUMINESCENT MATERIALS

The commonest method of obtaining luminous radiation from any substance is to increase its temperature to such an extent that luminous radiations are emitted. The emission of these luminous radiations is necessarily accompanied by the emission of large amounts of radiant-heat energy and usually of a certain amount of invisible ultra-violet radiation, with the result that, even with the most efficient type of electrical heating, only a fraction (about 4 per cent) of the amount of energy supplied is actually obtained in the form of luminous radiations.

The luminescent substances employed in cathode-ray tubes and for certain other purposes are of a totally different nature. Such substances effect the conversion of various types of radiant energy into luminous radiations, the conversion not being accompanied by the development of any sensible amount of heat. Luminescent substances of this nature emit luminous radiations when submitted to the action of various types of radiation, notably X-rays, cathode rays, radiations from radio-active substances, and ultra-violet radiations.

(3) FLUORESCENCE AND PHOSPHORESCENCE

Luminous radiation emitted by luminescent substances is of two types:—

(a) Fluorescence

An emission of luminous radiations which ends immediately the stimulus of exciting radiation has ceased to act, is known as fluorescence. According to Stokes' law, the wavelength of the fluorescent light is always greater than that of the exciting radiation.

(b) Phosphorescence

Phosphorescence differs from fluorescence in that it refers to light which continues to be emitted by a luminescent substance after the exciting radiation has ceased to act. The fluorescence of a luminescent body builds up almost instantaneously to a maximum intensity, which remains constant over a considerable period of time so long as the exciting radiation is unaltered. The phosphorescence occurs simultaneously with the fluorescence but, owing to its feebler intensity, it is only perceived when the fluorescence ceases. It also builds up more slowly than fluorescence during the first period in which the exciting radiation is acting. The intensity of phosphorescence diminishes continuously immediately upon the cessation of the exciting radiation. The rate of fall of luminescence is greatest at the beginning and decreases exponentially with lapse of time.

Fluorescence is the conversion of some form of energy into radiation in the visible spectrum. Phosphorescence is the emission of latent energy in this region.

According to some authorities, the distinction between fluorescence and phosphorescence is not a rigid one. A substance when fluorescing, can be regarded as being in a meta-stable condition, the luminescence being a phenomenon which is associated with a state of strain into which the molecule has been thrown owing to the

incidence of the exciting radiation. If the meta-stable condition of the molecule only persists so long as the exciting radiation is present, we have fluorescence. If, however, the molecule is not restored to its original condition immediately upon the cessation of the exciting radiation, the luminescence persists as phosphorescence.

It is a matter of experience that preparations which display fluorescence of maximum intensity always exhibit much less phosphorescence. Many phosphorescent preparations do not give fluorescence of the maximum intensity obtainable.

Fluorescence and phosphorescence are, however, differentially affected by various treatments. The most striking example of this is afforded by the extraordinary effect of the nickel "killer" on phosphorescence; this effect will be described later in the paper.

In the vast majority of practical applications of luminous bodies, it is fluorescence which is desired, the phosphorescence being either of no interest or, more frequently, definitely prejudicial. There appear to be two types of phosphorescence exhibited by luminescent substances; these may be regarded respectively as directly and indirectly excited.

(i) Directly-Excited Phosphorescence.

In the case of luminescent substances displaying directly-excited phosphorescence, the wavelength of the latter is the same as that of the fluorescence exhibited by the same body; e.g. zinc phosphate under cathode radiation displays a red fluorescence and, after the radiation has ceased to act on the substance, a red phosphorescence.

(ii) Indirectly-Excited Phosphorescence.

Indirectly-excited phosphorescence may be regarded as phosphorescence which is excited by the fluorescent light emitted by the substance itself. According to Stokes' law, therefore, the indirectly-excited phosphorescent light is always of greater wavelength than the fluorescent light. An example of this is afforded by certain types of zinc sulphides which can be made to exhibit brilliant blue fluorescence, the phosphorescence of the material being green and having the additional effect of modifying the colour of the fluorescent light emitted.

The phenomenon of directly and indirectly excited afterglow is very well displayed by the zinc-sulphide preparation R2, containing copper as a "phosphorogen."* This gives a brilliant blue-green fluorescence. The directly-excited response of this material is of so short duration as not to be measurable. The indirectly-excited response is of prolonged duration, and can be set up by exposure to radiation from cathode-ray tubes of various natures, including a tube coated with the zinc-sulphide R2 preparation. It is therefore clear that the fluorescence of R2 is capable of setting up phosphorescence in a sample of the same preparation, which has not been previously caused to fluoresce by any type of excitation.

(iii) Measurement of Phosphorescence.

Phosphorescence or, as it is frequently termed, "lag" or afterglow, if of short duration (up to, say, 1 000 microseconds), is very well measured by the method described by Bedford and Puckle.* Values of the time of phosphorescence for a number of different preparations determined by this method are given below:—

Material	Duration of directly-excited phosphorescence
Calcium tungstate ..	8 microsec.
Cadmium tungstate	8 microsec.
Willemite	2–8 millisec.
Zinc phosphate ..	about 0·25 sec.
Zinc sulphide with nickel "killer" ..	Too small to be measured (fraction of 1 microsec.)

It should be noted that the duration of the phosphorescence in any particular substance varies with the exact method of preparation employed, and that zinc sulphide with nickel "killer" addition† does not display any measurable phosphorescence.

In cases where the phosphorescence is of lengthy duration, i.e. minutes or hours, other methods have to be employed for its determination. Substances displaying phosphorescence of this nature are, however, outside the scope of this paper.

(4) MANUFACTURE AND CHARACTERISTICS OF LUMINESCENT SUBSTANCES

The production of luminescent substances is a very highly specialized branch of inorganic chemistry. Extraordinary precautions are necessary in order to obtain the best results. For example, it is essential that the materials should be as free as possible from every trace of certain substances, notably certain metals, which act as "poisons" and very greatly diminish the intensity of light emitted. The amount of impurity which is prejudicial is in some cases so small that the materials have to be prepared under what might be termed "aseptic" conditions, similar to those necessary in bacteriological work, in order to ensure the absence of all undesirable impurities.

(a) "Phosphorogens"

Certain substances, as, for example, calcium tungstate and cadmium tungstate, display their maximum luminescence when they are apparently perfectly pure; but in many cases, notably those of zinc sulphide and zinc-cadmium sulphide, zinc silicates, and zinc phosphates, very little luminescence is displayed unless an activator, commonly called a "phosphorogen," is present. The amount of the phosphorogen required is very small, generally about 1 in 10 000 to 1 in 100 000 parts by weight.

The majority of solid luminescent substances do not develop their special properties unless they are in crystalline form. The luminescent substances are therefore prepared in an extremely pure condition, the necessary phosphorogen is added, and the preparation is then heated to a high temperature either with or without flux, in order to induce the material to crystallize, after which the luminous properties become fully developed.

In certain cases, as, for example, the platinocyanides,

* See Section (4).

* *Journal I.E.E.*, 1934, vol. 75, p. 76.

† See page 13.

the luminescent substance is water-soluble and therefore can be crystallized from solution and is luminous without being heated. Heating would, in fact, destroy its luminescence.

(b) Nickel "Killer"

The fact has already been mentioned that, except in certain instances, the fluorescence of a luminescent body is desired and the phosphorescence, which often accompanies it, is undesirable or even fatal to the use of the substance. Zinc sulphide and zinc-cadmium sulphide are substances which, when prepared so as to be luminescent, display, when stimulated by all types of radiation, far greater intensity of luminescence than any other body so far produced. These substances do not display directly-excited phosphorescence of measurable duration. Unfortunately, however, the intense fluorescence displayed has always been accompanied by very considerable phosphorescence, which renders the material quite unsuitable for practical purposes—for example, the production of screens for X-ray work and, to a less degree, the use of the material in cathode-ray tubes for television purposes.

The authors have made the discovery that the phosphorescence exhibited by zinc sulphide can be inhibited by the presence of a minute trace of nickel, with the production of only a very slight diminution of fluorescence. The amount of nickel required is only about 1 part in 2 million, or even less. Nickel appears to be the only substance which acts in this manner, and this discovery has enabled the authors to produce luminescent materials for X-ray screens which have largely displaced the pre-existing types.*

This effect is of considerable importance in connection with fluorescent screens for cathode-ray tubes, in which phosphorescence of more than very low intensity is generally undesirable.

(c) Fluorescent Substances Employed

Large numbers of substances, both natural and artificial, exhibit luminescent properties under cathode-ray bombardment, but only a few have found practical application in cathode-ray tubes. The technique of manufacture of the latter precludes the use of many classes of substances; for example, as the tubes in the course of manufacture are heated to about 400° C., substances which would be damaged by such treatment cannot be employed. This naturally excludes bodies whose fluorescence depends upon the presence of water of crystallization, such as barium platinocyanide tetrahydrate.

The following are the principal substances which have been or are being employed for fluorescent screens in cathode-ray tubes:—

(i) Synthetic Willemite.

This is an artificially-produced zinc silicate which displays green fluorescence and some phosphorescence under cathode-ray bombardment. The material is specially sensitive to low-speed electrons corresponding to voltages of 250 to 300 volts.

* *British Journal of Radiology*, 1933, vol. 6, p. 404; and 1935, vol. 8, p. 184; also British Patent No. 19609/33.

(ii) Calcium Tungstate.

The fluorescence of calcium tungstate is blue-violet in colour and very actinic, and it is for this reason that it has been employed for the past 30 years in the manufacture of intensifying screens for X-ray purposes. For the same reason, the substance is employed in cathode-ray tubes when a photographic record of the trace on the fluorescent screen is required.

(iii) Cadmium Tungstate.

This substance has found application in cathode-ray tubes used for television owing to the fact that the fluorescence is of a very pale blue, so that the televised picture appears to be substantially black and white. This substance suffers from the drawback that high voltages have to be employed in order to produce a picture of adequate brilliancy.

Both calcium tungstate and cadmium tungstate have been largely or entirely superseded by special preparations of zinc sulphide and zinc-cadmium sulphide (see below), which are much more efficient.

(iv) Zinc Phosphate.

Zinc phosphate displays a red fluorescence and a directly-excited red phosphorescence. It finds some application in those instances in which a visible residual trace is required after the exciting beam has ceased to act on the screen.

(v) Zinc Sulphide and Zinc-Cadmium Sulphide.

Various varieties of zinc sulphide and zinc-cadmium sulphide are by far the most useful fluorescent substances so far developed for cathode-ray tubes. As already stated, the use of the nickel killer has enabled the objectionable phosphorescence to be eliminated and, as will be seen from the authors' photometric measurements (Figs. 1–4), the brilliancy of fluorescence produced by these substances with a given voltage far transcends that obtainable with any other luminescent chemical.

(5) CHARACTERISTICS OF THE FLUORESCENT SCREEN IN CATHODE-RAY TUBES FOR TELEVISION

The illumination of screens in cathode-ray tubes for television is of paramount importance, and it is essential to obtain the maximum brilliance with the minimum voltage owing to the fact that the cost of receivers increases very rapidly with increase of voltage.

(a) Saturation

Fluorescent substances under cathode-ray bombardment reach a saturation point after which no increase in either current or voltage effects any increase in brightness. The point at which various preparations exhibit saturation varies very greatly with the method of preparation employed. For example, certain varieties of zinc-cadmium sulphide exhibiting brilliant fluorescence at comparatively low voltages, saturate when the voltage is increased, whereas other preparations, differing only very slightly, show increasing luminosity over a far greater range.

Saturation measurements have been made on a number of substances. The measurements were made by Mr.

L. H. Bedford with a photoelectric photometer, and were of the following two kinds.

(i) " Raster " Saturation.

In this type of saturation the size of the " raster " (i.e. the illuminated area covered by the scanning spot, or the scanning field) is progressively reduced without alteration of the size or the intensity of the spot. The standard conditions for these tests were 3 000 volts, 100 microamps., i.e. 0·3 watt in the beam. The raster size was reduced in steps from its normal value of approximately 80 mm × 60 mm to approximately 30 mm × 18 mm, representing a variation of raster rating of 0·0062–0·055 watt per cm^2. None of the screen materials showed saturation even under these high intensities, which are enormously higher than anything contemplated in television; for the latter, a maximum raster rating would be of the order of 0·001 watt per cm^2.

(ii) Spot Saturation.

In order to test for spot saturation, the raster was maintained at its normal size whilst the size of the spot was varied without alteration of the ray current and voltage. It was not possible to make accurate measurements, as it was impracticable to determine accurately the size of the spot in its focused condition. It may be assumed, however, that the spot area under the standard conditions mentioned would be of the order of 1 mm^2; the spot rating in the focused condition would therefore be 30 watts per cm^2. For an increase in area of some 25 times, an increase in luminosity of the order of 35 per cent was observed. This indicates that the spot is only slightly supersaturated.

(b) Intensity of Illumination

A number of photometric measurements have been made upon cathode-ray tubes coated with various fluorescent materials, the results of which are given in Figs. 1–4. In carrying out these determinations, the authors employed the method they had previously developed for similar determinations of the intensity of illumination of X-ray screens.* Owing to the fact that in the majority of instances the fluorescent light is coloured, whereas the light emitted by the comparison lamp is white or nearly so, a flicker photometer—the most satisfactory type for comparing lights of various colours —has been employed in carrying out this series of tests. In each case, the photometric determinations have been made in two ways:—

First, the curves in Fig. 1 were obtained by maintaining the current, i.e. the number of electrons in the stream, constant and varying the applied voltage, thus varying the velocity of the electrons.

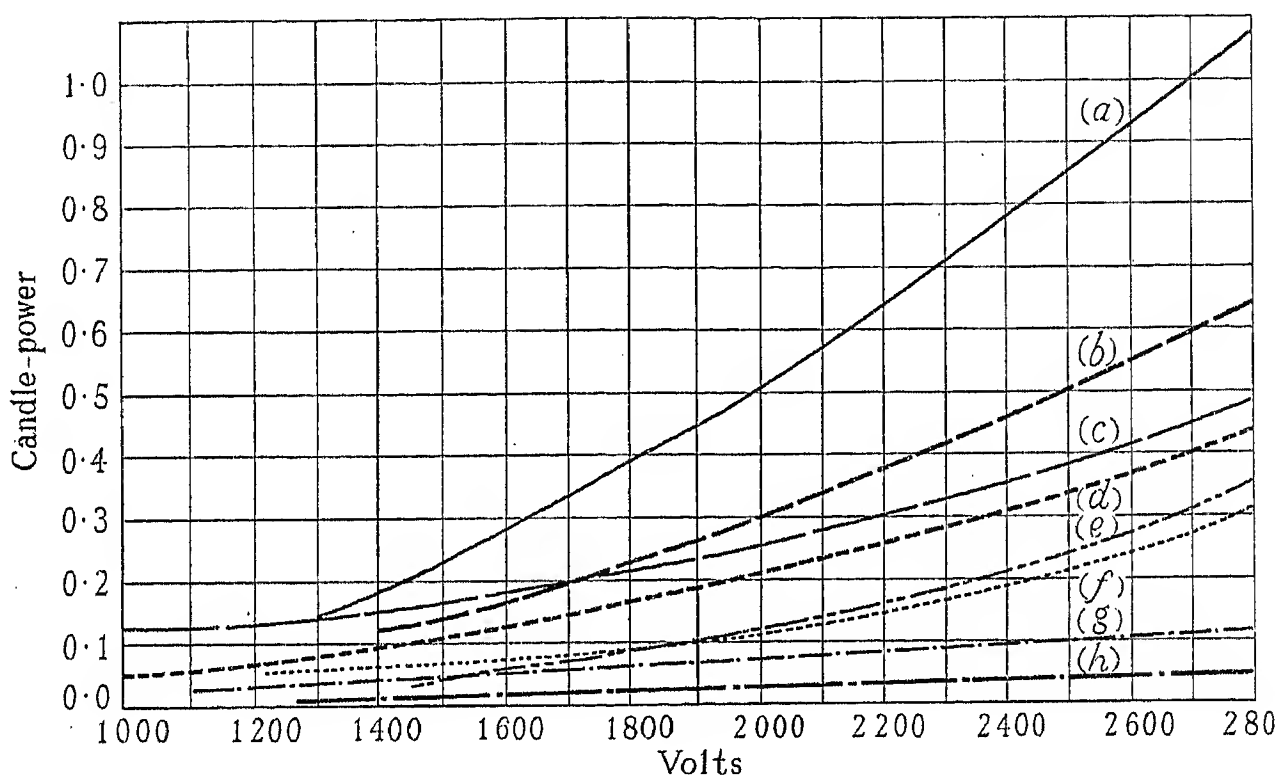


Fig. 1.—Curves obtained by maintaining current constant at 150 microamps. and varying applied voltage.

(a) Preparation Z 23 (zinc sulphide and zinc-cadmium sulphide).
(b) Zinc sulphide U 36.
(c) Zinc sulphide G 86.
(d) Zinc-cadmium sulphide B 11.
(e) Zinc-cadmium sulphide (foreign preparation).
(f) Willemite.
(g) Cadmium tungstate.
(h) Zinc phosphate.

Second, the curves in Fig. 2 were arrived at by maintaining the voltage, and hence the speed, constant and varying the current.

The tests have been carried out with the following materials: willemite, cadmium tungstate, zinc phosphate, zinc sulphide U 36 (giving nearly white fluorescence), zinc-cadmium sulphide B 11 (giving pale primrose fluorescence), zinc sulphide G 86 (giving pale blue fluorescence), and preparation Z 23 (a mechanical mixture of zinc sulphide and zinc-cadmium sulphide, which displays a brilliant white fluorescence of high intensity).

Inspection of these curves shows that:—

(i) The greatest intensity of luminosity at every given

* *British Journal of Radiology*, 1925, vol. 21, p. 104; and 1933, vol. 6, p. 404.

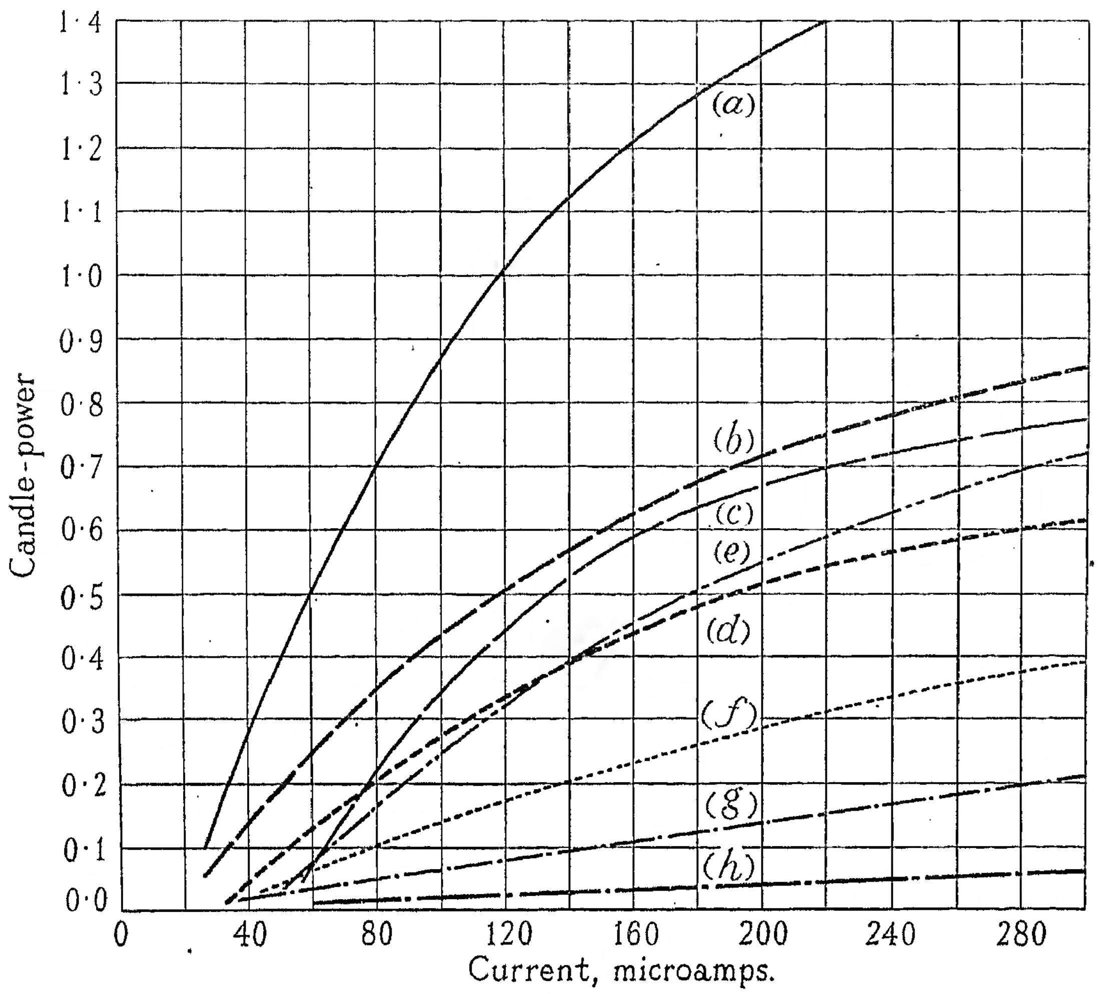


Fig. 2.—Curves obtained by maintaining voltage constant at 2 800 volts and varying current.

(a) Preparation Z 23 (zinc sulphide and zinc-cadmium sulphide).
(b) Zinc sulphide U 36.
(c) Zinc sulphide G 86.
(d) Zinc-cadmium sulphide B 11.
(e) Zinc-cadmium sulphide (foreign preparation).
(f) Willemite.
(g) Cadmium tungstate.
(h) Zinc phosphate.

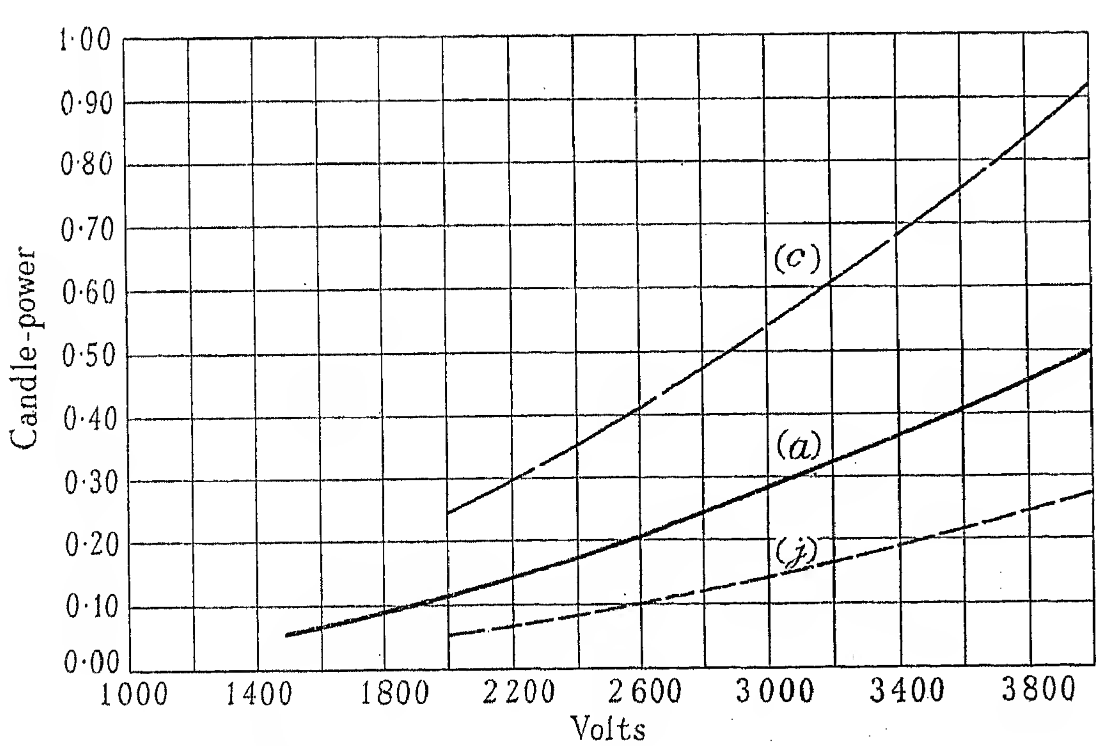


Fig. 3.—Curves obtained by photoelectric cell method. Current maintained at 100 microamps., voltage varied.

(a) Preparation Z 23 (zinc sulphide and zinc-cadmium sulphide).
(c) Zinc sulphide G 86.
(j) Zinc-cadmium sulphide (foreign preparation).

voltage is displayed by preparation Z 23. Zinc sulphide U 36 gives the greatest luminosity of any single preparation without admixture.

(ii) There is no evidence of saturation at the highest voltage employed in the measurements, namely 2 800 volts.

(iii) The zinc-sulphide preparations and willemite are more sensitive to low-speed electrons than cadmium tungstate and zinc phosphate.

(iv) Zinc phosphate gives a quite brilliant red fluorescence, but the actual luminosity is very small and is only slightly increased with increase of voltage or current density.

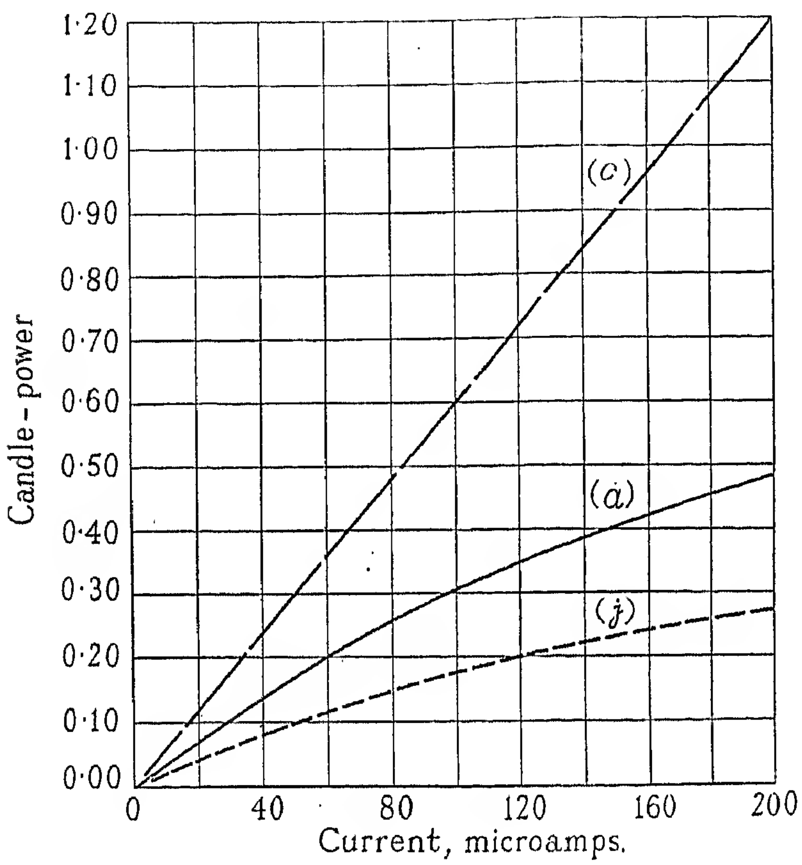


Fig. 4.—Curves obtained by photoelectric cell method. Voltage maintained at 3 000 volts, current varied.

(*a*) Preparation Z 23 (zinc sulphide and zinc-cadmium sulphide).
(*c*) Zinc sulphide G 86.
(*j*) Zinc-cadmium sulphide (foreign preparation).

A number of the fluorescent materials examined by the authors were also examined by Mr. Bedford, by the photoelectric cell method. An Oxford caesium vacuum cell was employed. The screen was placed 112 mm from the centre of the photocell window in all cases. All readings were purely comparative and were plotted directly in terms of galvanometer deflection, the calibration of the galvanometer being 185 divisions per microamp. As the spectral sensitivity of the cell is not accurately known, it was not considered desirable to attempt to refer the measurements to a standard candle-power.

The results of the determination with the photoelectric cell are shown graphically in Figs. 3 and 4. Inspection of these curves shows:—

(i) Owing to the high sensitivity of the photoelectric cell to the blue end of the spectrum, preparation G 86 appears to give the greatest luminosity. This does not accord with visual observations, as there is no doubt at all that visually the white fluorescing zinc-sulphide preparation, Z 23, is considerably brighter.

(ii) It will be observed that the curves obtained with the photoelectric cell show the same general characteristics as those arrived at by the use of the flicker photometer. In all cases in which the anode current is maintained constant and the voltage varied, the curves show a slight convexity towards the abscissæ. On the other hand, observations in which the current is maintained constant and the voltage varied, give curves which show a slight concavity.

(c) Proportion of Light Transmitted through the Screen

The values of the illumination of the screen at the surface upon which the electrons impinge, and at the surface next the glass, are not the same. The difference will depend upon the thickness of the screen, the transparency of the fluorescent material, its grain size, and the nature of the medium employed for fixing the material to the glass. The surface upon which the cathode rays impinge is always brighter than the surface next to the glass, which is the one upon which fluorescent effects are observed. If a reflector of white paper is placed upon the surface of the glass, the amount of light emitted from the inner surface is again considerably increased. This illumination is equal to the total amount of light emitted, less that lost by absorption in the glass and by imperfect reflection by the paper surface.

The following are the results of measurements made to ascertain the illumination values under these various conditions:—

Zinc sulphide and zinc-cadmium sulphide mixture, Z 9, at 2 800 volts, 150 microamps. Illumination of screen viewed through base of tube, 0·94 candle-power; illumination of surface upon which cathode radiation impinges, 1·32 candle-power; illumination of surface upon which cathode radiation impinges, with white paper reflector, 1·63 candle-power.

The illumination of a screen prepared from the mixture of zinc sulphide and zinc-cadmium sulphide, Z 23, in metre-candles, when used for television reception, is given by $\pi C/A$, where A = area of raster in m^2, and C = observed candle-power. According to the authors' measurements, $C = 1\cdot 08$ at 150 microamps. and 2 800 volts, and $A = \frac{1}{20}$ on a screen of 25 cm × 20 cm illuminated surface. The illumination is therefore 68 metre-candles. This compares quite favourably with the illumination of the screen in a home cinema, an average figure for which may be taken as 22 metre-candles.

Von Ardenne* gives the results of a number of measurements of illumination of various fluorescent substances excited by cathode rays, and it appeared to be desirable to ascertain whether the values given by him were in accordance with those obtained by the authors. Von Ardenne kindly provided a small portion of green fluorescent zinc sulphide for comparison. His value for this material is 3·5 Heffner candles per watt.

* *Zeitschrift für technische Physik*, 1935, vol. 16, p. 3.

According to the authors' measurements, the candle-power—measured through the glass from the front—of a screen coated with this material is 0·80 with a current of 100 microamps. at 2 800 volts, i.e. 2·89 international candles or 3·21 Heffner candles per watt. This, having regard to the different methods employed in the manufacture of cathode-ray tubes and in the measurement, represents remarkably close agreement.

(d) Colour

The colour of the fluorescence is of considerable importance in television. Brilliantly coloured images do not make a general appeal. An image which is black and white, or nearly so, is preferred for general purposes. A very slight amount of warm tone such as pink, yellow, or sepia, is not so objectionable, but a greenish-white tint is not acceptable as it gives the picture a very cold appearance. It should be noted that the colour of a picture is its colour at low intensity. The bright portions are always substantially white in appearance. At high intensity of the raster, preparation U 36 appears to be quite white, but the picture as a whole displays a pale bluish-green tint.

Zinc sulphide and zinc-cadmium sulphide can now be so prepared as to emit fluorescent light of practically any colour. This is effected by varying the phosphorogen employed in the preparation of the substance and also the relative proportions of zinc sulphide and zinc-cadmium sulphide present in the preparation. For example, zinc sulphide R 2 containing copper phosphorogen exhibits a brilliant blue-green fluorescence. If silver is employed as phosphorogen, however, the fluorescence is blue or blue-violet. If varying proportions of cadmium sulphide are added to zinc sulphide containing copper as phosphorogen, the colour of fluorescence can be varied from red through orange and yellow to green. Cadmium sulphide by itself is not luminescent, but it crystallizes isomorphously with zinc sulphide and acts as a colour filter, as well as modifying the character of the luminescence.*

(e) Production of White Fluorescence

Preparations displaying white fluorescence can be obtained by mixing together two or more fluorescent substances displaying highly coloured fluorescence, the colours being selected so that a white is obtained; as, for example, by combining blue and a reddish-orange fluorescence. This method was employed by the authors a number of years ago for the production of compositions which would display white fluorescence when stimulated by ultra-violet radiation.

This method of obtaining white fluorescence is sometimes open to the objection that the spectral response (see below) of the luminescent substance varies with the intensity of the current. Certain mixtures which are white at any particular voltage will therefore probably appear somewhat coloured when the current intensity is altered to any considerable extent, although this does not appear to be the case with mixtures of zinc sulphide and zinc-cadmium sulphide.

Up till quite recently, cadmium tungstate was the only substance the fluorescence of which was only slightly coloured. It is actually pale blue. As shown in Figs. 1 and 2, cadmium tungstate is very inefficient compared with zinc sulphide, and it is therefore obvious that if a zinc-sulphide preparation could be produced displaying white fluorescence, this would be of interest. The authors have developed a zinc sulphide of this nature, U 36, the colour of fluorescence of which is substantially white.

The spectra of fluorescence of various preparations are given in Figs. 5, 6, 7, 8, 9A, 9B, 10A, 10B, 11A, 11B, 12, and 13 (see Plate 1, facing page 24). The relatively clear band 4 900–5 100 Å on all the spectra is a characteristic of the photographic emulsion, which does not respond well to light of this wavelength. This is shown in Fig. 5, which is a spectrum of candle light.

The spectrograms were made at different values of current density, in order to demonstrate the effect of this quantity upon the colour of emission.

It will be observed that the fluorescent spectrum of the various substances in each case consists of one or more bands. In the case of preparations in which only one phosphorogen is present, as a general rule the fluorescent spectrum consists of one band only. If more than one phosphorogen is present, then another band usually makes its appearance.

Mixtures of fluorescent substances also give two or more bands which coalesce into a continuous spectrum if the mixtures have been adjusted so that the light of the fluorescent mixture is white. It will be observed that the spectra of the zinc-sulphide preparations G 86 and B 11 are complementary, and thus a mixture of these two preparations should and does give a continuous spectrum.

The limits of the bands for the various substances examined are as follows:—

Cadmium tungstate.—A well-defined band 3 900–4 900 Å, and a slightly-defined band 5 200–6 000 Å.

Willemite.—A well-defined band 4 900–5 500 Å.

Zinc phosphate.—A well-defined band 5 800–6 400 Å.

Zinc sulphide, U 36.—A preparation giving substantially white fluorescence; the first band is 4 200–5 000 Å, then there is a slight break, and the band continues (5 200–5 600 Å).

Zinc sulphide, G 86.—The band of this preparation extends into the ultra-violet. It starts at 3 700 Å, is well defined at 4 000 Å, and continues to 4 800 Å.

Zinc sulphide, B 7.—This preparation gives a fairly continuous spectrum from 4 600 Å to 6 500 Å, but there is not much radiation at 5 000–5 200 Å and 6 300–6 400 Å.

Zinc sulphide, B 11.—A band extends from 4 300 Å to 6 400 Å, with slightly lighter patches at 5 700–5 800 Å and 4 800–5 000 Å.

Mixture (Z 23) of G 86 and B 11.—This gives practically a continuous spectrum extending from 3 900 Å to 6 600 Å. The falling-off around 5 000 Å is due, as stated above, to the characteristics of the photographic emulsion.

It is a matter of ocular observation that fluorescence is always more coloured at low current densities. Increase in current density tends to make the fluorescence appear white in colour. In part, this is undoubtedly a

* A. A. Guntz: *Annales de Chimie*, 1926, vol. 5, p. 374.

light-intensity effect, but the spectrograms clearly show that this is not entirely the case. This effect is not shown by the G 86–B 11 mixture, which displays a neutral grey tint at low intensities.

The fluorescence spectra of U 36 and B 11 are nearly continuous. There is, however, very little radiation at the red end of the spectrum of U 36, which accounts for the very slight pale-blue tint exhibited by this preparation. In the case of B 11, the radiation is missing at the violet end of the spectrum, and this preparation exhibits a pale primrose fluorescence.

(f) Contrast

In high-vacuum tubes, which are the only ones employed in actual practice, the nature of the luminescent material is without effect upon the contrast except in the case of materials displaying strong phosphorescence. Such materials are of course quite unsuitable for television. This is in contradistinction to the behaviour of similar fluorescent substances used for X-ray screens. In this case the contrast is largely dependent upon the nature of the fluorescent substance, and particularly upon its relative response to hard and soft radiation.

In television tubes the contrast is controlled by varying the current-density ratio between the regions of maximum and minimum illumination.

(g) Definition and Fine Grain

The scanning spot of a 240-line picture 8 in. high is 0·9 mm in diameter, and generally speaking, therefore, the particle size of the fluorescent substance is immaterial as it is always far less than this; the particle size being usually considerably less than 0·1 mm in diameter. In spite of this, however, fine particle size is desirable, as it facilitates the production of a screen which is uniformly coated and which therefore exhibits a uniform degree of illumination over the whole of its surface. Very fine particles also require less adhesive material to fix them on the glass, than is necessary in the case of coarse particles.

Phosphorescence or afterglow tends to reduce definition and contrast.

(h) Lasting Qualities

The fluorescent material of which the screen is composed must maintain the brilliancy of its fluorescence unimpaired during the average life of the cathode-ray tube, which should be well in excess of 1 000 hours. At the intensities involved in reception, all zinc sulphides give the required life. Luminescent substances behave variously when subjected to the prolonged action of radiations of different kind. For example, zinc sulphide if mixed with radioactive material to form a self-luminous compound, undergoes a steady depreciation in luminosity when bombarded by α-particles, but zinc sulphides and the tungstates do not undergo any depreciation in luminous characteristics when subjected to the prolonged action of X-radiation.

(6) CATHODE-RAY TUBES FOR PURPOSES OTHER THAN TELEVISION

Fluorescent screens used in cathode-ray tubes for purposes other than television are frequently required to display special characteristics; for example, it is sometimes desired to obtain a persistent visual trace of fluorescence after the exciting source has ceased to act, as, for example, in the Cossor–Robertson electro-cardiograph. The material used must therefore be one which is prepared specially, in which the phosphorescence instead of being suppressed is stimulated as much as possible. Zinc phosphate (giving a red afterglow) or zinc sulphide with copper phosphorogen (giving a brilliant green afterglow) can be employed for this purpose, but the latter, having a much longer afterglow, is preferred.

In many applications of cathode-ray tubes it is desirable to be able to photograph the trace on the fluorescent screen, and in this instance, therefore, the colour of the fluorescence should be as actinic as possible. Calcium tungstate is usually employed for this purpose, but it is now being replaced by special grades of zinc sulphide with silver phosphorogen which display brilliant blue fluorescence of very high actinic quality.

(7) PRACTICAL DETAILS

Method of Coating the Fluorescent Screen

Fluorescent powders are distributed upon the base of the tube by coating the latter with an adhesive substance and blowing the fluorescent powder on to the adhesive surface, the surplus powder which does not stick on being removed by shaking. Alkaline silicates are most commonly employed as the adhesive substance, as, unless they are present in excess, these materials are without detrimental action upon the fluorescence. Potassium silicate is preferred to sodium silicate by some workers, and in either case the preparation should preferably be low in alkali content.

It is important that the amount of adhesive employed should be as low as possible, so that in effect the fluorescent particles are simply anchored in position by attachment at one spot of their surface. If excess of silicate is present, this can react with the fluorescent materials employed, with resulting degradation of their luminescent qualities.

Efficiency of Luminescence

The efficiency of luminescence of fluorescent bodies excited by cathode radiation compares favourably with that of light obtained by means of increase of temperature, as in ordinary electric lighting. In the case of the preparation Z 23 the efficiency of illumination is about 3·2 candle-power per watt of energy input.

Intrinsic Brightness

The intrinsic brightness of the scanning spot which is produced by a cathode-ray beam of very high intensity is very great. In the case of a television transmitting tube the scanning spot is 0·3 mm in diameter and has a candle-power of 1·2. Hence its luminosity is 17 candles per mm^2. The intensity of illumination of the filament in a tungsten vacuum lamp is 1·25 candles per mm^2, and in the case of the gasfilled lamp 5 to 13 candles per mm^2, according to the type and size of the lamp. The intrinsic illumination of the scanning spot is thus higher, but it is still very much below that of the arc crater of a plain carbon arc, which is of the order of 170 candles per mm^2.

(8) FUTURE DEVELOPMENTS

Research on luminescent materials during the last 2 or 3 years has resulted in the production of luminous sulphides suitable for cathode-ray tubes, the efficiency of which is about 3 times as great as the highest value previously obtainable. The maximum amount of light now obtainable amounts to 4 or 5 per cent of the energy input. It is impossible to say whether this figure can be materially increased in the future, but there is still ample scope for development. The production of luminescent substances which are specially sensitive to low-speed electrons should lead to further improvement, as high voltages entail greater expense in the manufacture of television apparatus.

The authors desire to express their very best thanks to Messrs. A. C. Cossor, Ltd., for preparing cathode-ray tubes coated with the various fluorescent preparations and for the loan of the apparatus for their employment. They also desire to accord special thanks to Mr. L. H. Bedford for his most valuable criticism and assistance.

[The discussion on this paper will be found on page 25.]

THE COMPARATIVE PERFORMANCE OF GAS-FOCUSED AND ELECTRON-LENS-FOCUSED OSCILLOGRAPHS AT VERY HIGH FREQUENCIES

By L. S. PIGGOTT, B.Sc.(Eng.), Graduate.

(*Paper first received* 9*th January, and in final form* 10*th February,* 1936; *read before the* WIRELESS SECTION, 4*th March,* 1936.)

SUMMARY

The focusing and other properties exhibited by gas-focused and electron-lens-focused oscillographs when radio frequencies and ultra-high frequencies of deflection are used, are compared and contrasted. The superior focusing properties of, and absence of origin distortion in, the electron-lens-focused tube are demonstrated.

Characteristics peculiar to either type of tube are discussed, and some phenomena common to both types, when used at very high frequencies, are described.

Finally, two applications of the cathode-ray oscillograph at very high frequencies are suggested.

TABLE OF CONTENTS

(1) INTRODUCTION

The gas-focused cathode-ray oscillograph suffers from two well-known disadvantages. These are (*a*) "origin distortion," or lack of sensitivity near the axes of co-ordinates of the trace, at all frequencies of deflection; and (*b*) loss of focus when the beam is deflected at frequencies above about 0·2 Mc/s. Both these characteristics are caused by the focusing gas, and can be controlled, to a limited degree, by alteration of the gas used and of its pressure. The choice of the best oscillograph for use at any one particular frequency is always a matter of compromise, since origin distortion increases as the focusing at high frequencies is improved.*

The recently-developed high-vacuum electrostatically-focused oscillograph does not suffer from these shortcomings of the gas-focused tube, since its focusing depends entirely upon the static operating potentials, and does not require the ionization of a gas, a process which takes time, and accounts for the focus failure of the gas-focused tube at high deflecting frequencies. The high vacuum of the electrostatically-focused type also ensures absence of origin distortion. This type of tube, however, is not ideal for all purposes. In the case of the particular sample used by the author the focusing was not as good, at audio frequencies, as that of the gas-focused tube. But this disadvantage is not serious, as the difference is only slight.

* J. T. MacGregor-Morris and J. A. Henley: *Journal I.E.E.*, 1934, vol. 75, p. 487.

A more serious defect of the electron-lens tube manifests itself when one deflector plate of a pair must be earthed (i.e. connected directly to the last anode). Owing to the change in effective potential just beyond the last anode, when the instantaneous deflecting potential is large, the "focal length" of the last electron-lens is altered and the beam becomes defocused at the extremes of its deflection. There are occasions when it is impossible to do other than earth one deflector plate of a pair, and in such cases this defocusing effect, which occurs at all frequencies of deflection, makes accurate working difficult. Accordingly, the author has devised a method which partially corrects this effect, and may be used at audio and radio frequencies. This will be discussed in Section (2) of the paper.

If it is not imperative that one plate of a pair be earthed, then push-pull connection to the deflecting plates should be used wherever possible, as this defocusing effect does not occur under these conditions.

(2) PERFORMANCE AT RADIO FREQUENCIES

In order to study the improved focusing of the electron-lens tube at radio frequencies, a series of photographs was taken of a trace in one direction only, at frequencies between 0·25 and 8 Mc (1 200 m to 37·5 m), both on the electron-lens tube and on two gas-focused tubes, one with helium as the focusing gas and the other with argon. These photographs, shown in Figs. 1, 2, and 3 (Plate 2, between pages 24 and 25), indicate that the focusing of the electron-lens tube at these frequencies is comparable with that of gas-focused tubes at 50 cycles per sec. As far as can be judged from the photographs, there is no loss of focus when the high-vacuum tube is used at radio frequencies. Such a result is what one would expect.

The electron-lens tube was calibrated at several frequencies; the total trace length was measured, and the peak deflecting potential was measured by means of a diode peak voltmeter. From the calibrations given in Figs. 4 and 5 it is apparent that, within the limits of experimental error, there is no origin distortion with this tube at these frequencies. A further demonstration of this useful property of the electron-lens tube is given in Fig. 6 (Plate 2); in this case the same high-frequency potential was applied to both pairs of plates, deflecting potential was applied to both pairs of plates, but a bias, variable in steps, was added to the X-deflecting potential. There is no sign of the kinks in the traces which are so familiar with the gas-focused tube used under similar conditions.*

* This method was used by Prof. MacGregor-Morris and Mr. Henley to show the effect of origin distortion in gas-focused tubes (see *Journal I.E.E.* 1934, vol. 75, p. 487).

Mention has been made in the Introduction of a means of correcting the defocusing which occurs at the edges of a large trace when one deflector plate of a pair must be earthed. It was found that by variation of the potential on the second anode of the oscillograph any particular point in a one-direction trace could be focused (Fig. 8, Plate 2). It therefore seemed probable that if the deflecting potential, or a fraction of it, were to be superimposed on the steady potential on the second anode, the focusing might automatically adjust itself at every point of the trace. A condenser potential-divider was used, and a high-frequency choke inserted in the lead to the second anode (Fig. 7). It was found that for a simple trace in one direction only, the re-focusing was perfect, as can be seen from Fig. 8. The addition of a time-

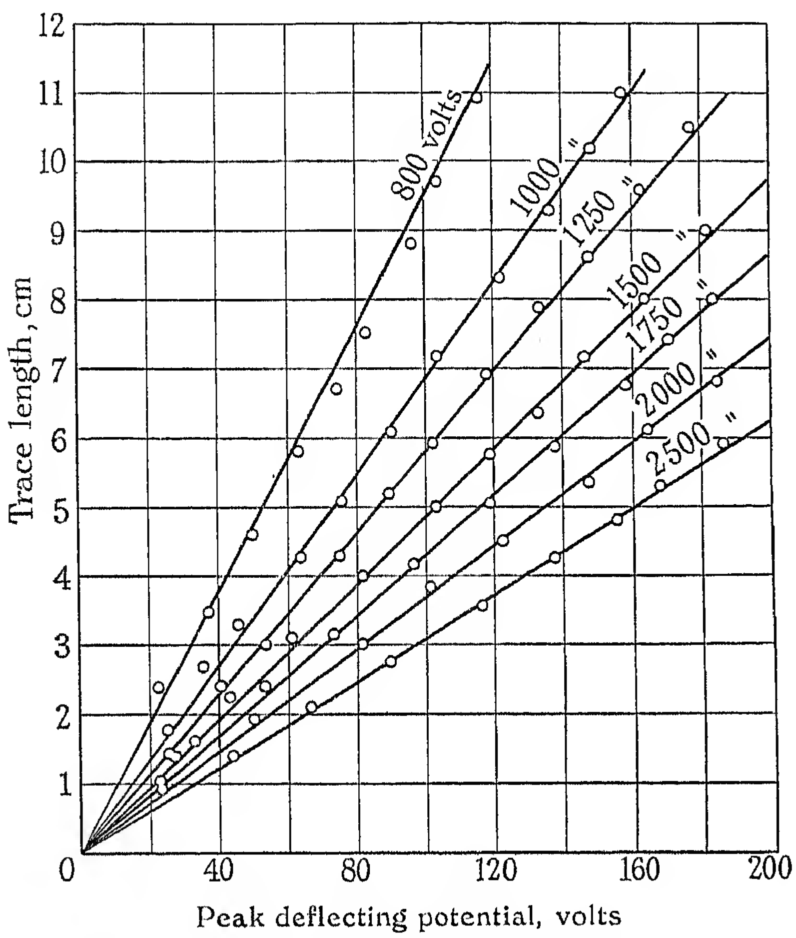


Fig. 4.—Calibration of electron-lens oscillograph at 0·5 Mc.

sweep in the X-direction tended to destroy the perfection, but the focusing was still better than it had been before the correction was applied (see Figs. 9 and 10).

The obvious disadvantage of the method lies in the condenser potential-divider, which reduces the effective input impedance of the oscillograph. The two condensers can, however, be made quite small. For obtaining the traces shown in Figs. 8, 9, and 10, the capacitance of the potential divider employed was of the order of 20 $\mu\mu$F, while the capacitance of the tube itself is about 0·7 $\mu\mu$F.

Whenever possible, push-pull connection should be used to both pairs of plates, as it avoids the modulation of one deflection by the other, an effect which gives a trapezoidal trace, as can be seen from Figs. 9 and 10.

(3) PERFORMANCE AT ULTRA-HIGH FREQUENCIES

When the frequency is raised much farther, the gas-focused tube begins to regain its lost focusing properties, but not completely, even at a frequency as high as 1 350 Mc. The focusing of the electron-lens tube would appear to be unchanged, even at this frequency. Figs. 11 to 14 (Plate 3) show traces at various very high frequen-

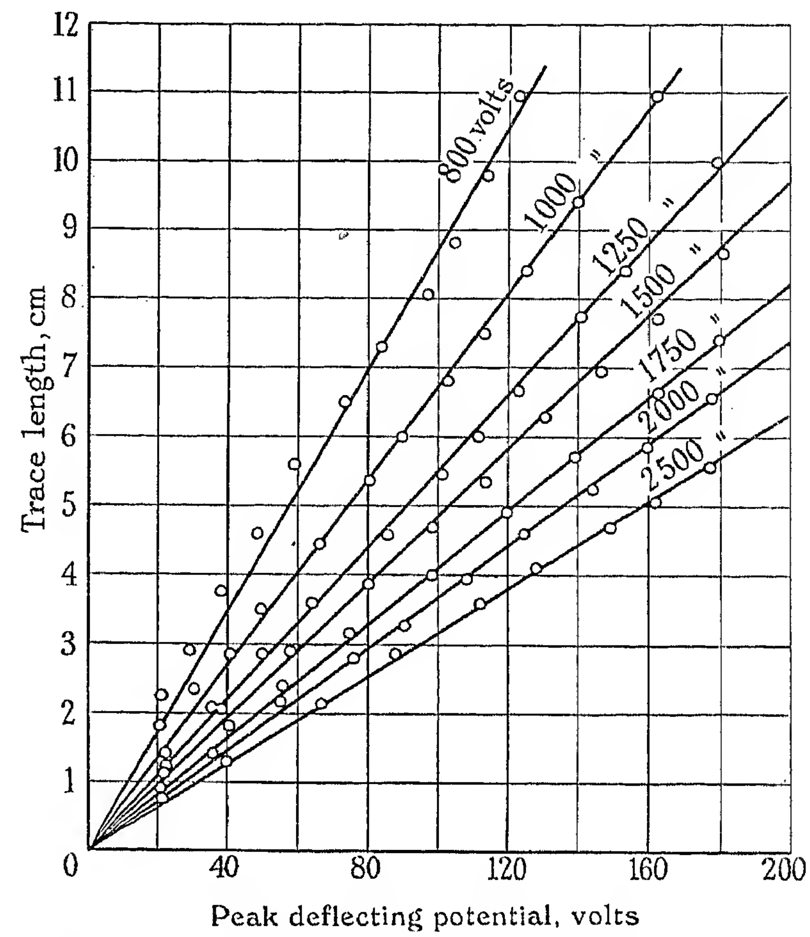


Fig. 5.—Calibration of electron-lens oscillograph at 1 Mc.

cies, obtained on all three of the tubes tested. The excellent focusing properties of the high-vacuum tube make it a useful instrument, even at these frequencies, and it was considered worth while to study further its properties at high writing speeds.

At frequencies above about 10^8 cycles per sec. there occur two important effects, first demonstrated by Hollmann,* and usually called the Hollmann effects. These

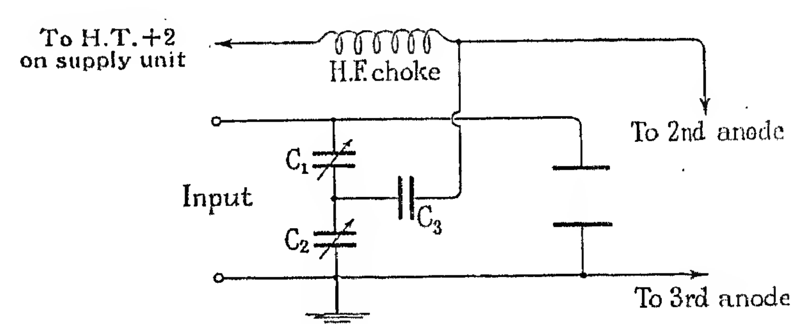


Fig. 7.—Circuit used for focus correction.

are: (*a*) the Hollmann sensitivity effect, and (*b*) the Hollmann phase effect. Both are due to the fact that the electrons in the beam travel at a finite speed.

If the time of transit of an electron past a deflecting plate is comparable with the period of the deflecting potential, then, while under the plate, the electron is subject to an electric field which varies appreciably

* *Wireless Engineer*, 1933, vol. 10, pp. 430 and 484.

during the time of passage of the electron past the deflecting plates. Thus, if the potential applied to the plates is of the form

$$V = f(t),$$

and the electron first comes under the influence of the deflecting field at time t, then the transverse velocity given to the electron during its passage past the deflecting plate is

$$\frac{e}{m} \cdot \frac{1}{d} \int_0^T f(t + \delta) d\delta,$$

where d is the perpendicular distance between the deflecting plates, and T is the time of passage past them, and is equal to l_1/v_0, where l_1 is the length of the plate, and v_0 is the velocity of the electrons along the axis of the tube. Then the deflection of the spot on the fluorescent screen is given by

$$\frac{l_2}{mv_0 d} \int_0^{l_1/v_0} f(t + \delta) d\delta = S_0 \int_0^{l_1/v_0} f(t + \delta) d\delta,$$

where l_2 is the distance between the deflecting plates and the fluorescent screen, and S_0 is the static sensitivity, or the sensitivity at low frequencies.

Hollmann has shown that when

$$V = V_0 \sin \omega t,$$

then the deflection is given by

$$V_0 S_0 \sin \omega(t + T) \frac{\sin (\omega T/2)}{(\omega T/2)}$$

The sensitivity thus passes through successive maxima and minima, the peaks in the frequency/sensitivity curve becoming steadily lower as the frequency is raised.

As the four deflecting plates are not arranged with their centres in one plane (in order to avoid mutual interaction), an electron takes a time z/v_0 to travel the distance z from the centre of one pair of deflecting plates to the centre of the other pair. This corresponds to a phase angle $\omega z/v_0$ added to, or subtracted from, that already existing between V_X and V_Y, the angle having a different value for every frequency. This effect is the Hollmann phase effect. It may be demonstrated by applying the same deflecting potential to both pairs of plates. At low frequencies, a straight line inclined at an angle of 45° to the axes results, but at ultra-high frequencies, owing to the Hollmann phase effect,* the trace may be an ellipse, or a circle (as shown in Fig. 11), or a straight line.

These phenomena may be distinctly disadvantageous, especially as they both vary with frequency. When the wave-form of the deflecting potential is non-sinusoidal, the deflection of the beam does not follow the deflection potential. In other words, the tube is introducing both frequency distortion and phase distortion.

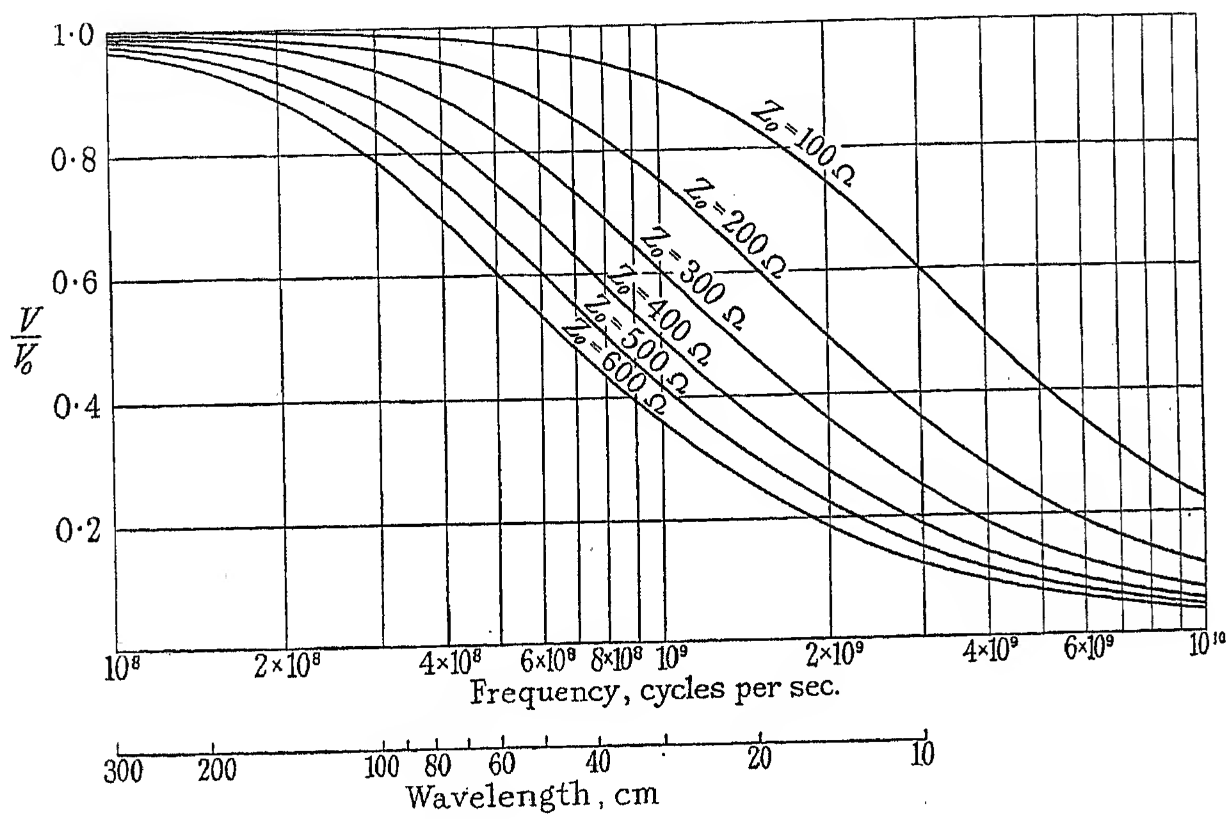


Fig. 15.—Curves showing effect of deflecting-plate capacitance on sensitivity. (Calculated for a capacitance of 0·7 $\mu\mu$F.)

The effect of the capacitance of the deflecting condenser on the sensitivity of the tube at very high frequencies will now be discussed. It is shown, in Appendix I, that if the capacitance between the deflecting plates is C, and the line supplying the deflecting potential to them is of characteristic impedance Z_0, then the effective deflecting potential is

$$\frac{V_0}{\cos (2\pi l/\lambda) + Z_0 C\omega \sin (2\pi l/\lambda)}$$

where l is the length of the feeder and V_0 is the potential difference at the supply end. This may be expressed as the potential difference at a distance y from the end

* As no attempt was made to keep the deflecting potential constant, the photographs do not demonstrate the Hollmann sensitivity effect.

of an open-circuited feeder of length $(l + y)$, where $y = \frac{\lambda}{2\pi} \arctan (Z_0 C\omega)$. In order to obtain maximum potential at the deflecting plates, $(l + y)$ must be an integral number of half-wavelengths. The maximum obtainable deflecting potential is then

$$\frac{V_0}{\sqrt{[1 + (Z_0 C\omega)^2]}}$$

In the Cossor oscillographs used by the author, the deflecting-plate connections are brought out to the base of the tube through parallel feeders. From measurements on some X-ray photographs, the characteristic impedance of the line was calculated to be about 500 ohms. The capacitance of the deflecting condenser is about $0 \cdot 7\ \mu\mu F$. These figures give $y = 4 \cdot 4$ cm at $\lambda = 22$ cm. The effective deflecting potential under these conditions is only $0 \cdot 32$ of the p.d. at voltage antinodes on the feeder line. From this practical illustration, the importance of this effect may be judged.

Fig. 15 shows the variation of this effect with frequency, and feeder impedance, for a terminating capacitance of $0 \cdot 7\ \mu\mu F$. It indicates the necessity of using a feeder of low characteristic impedance. It is thus advisable to use closely spaced wires, as radiation loss is also thereby reduced.

The leads to the X-plates are at the ends of a diagonal, and those to the Y-plates at the other corners, of a square. If the assembly is such that the leads are not exactly at the corners of a square, then there is a small mutual inductance between the two feeders. It is possible under these conditions to obtain, at very high frequencies, a deflecting potential in one circuit, due to currents induced in it from the other circuit. This effect can usually be overcome by so arranging the leads outside the tube that there is an effectively equal and opposite mutual inductance between the two deflecting-plate circuits.

The slight ellipticity of the trace at 270 Mc, shown in Fig. 14, is due to this cause. The X-plates were short-circuited at the base of the tube, and the X-deflection is due almost entirely to induced e.m.f.'s from the Y-circuit. The effect was reduced, in the traces at 150 Mc and $83 \cdot 4$ Mc respectively, by adjustment of the leads outside the tube.

(4) APPLICATIONS OF THE OSCILLOGRAPH AT VERY HIGH FREQUENCIES

There would appear to be very few applications for a cathode-ray oscillograph at frequencies of the order of 1 000 Mc. The chief obstacles in the way of its use are the Hollmann effects and the difficulty of obtaining a suitable high-speed repeating time-base.

The Hollmann phase effect can be overcome by a special tube produced by Von Ardenne.* Some use can be made of this effect, however, in a wave-form check on an unmodulated ultra-short wave oscillator. If the X- and Y-plates are paralleled, then, if the oscillator is giving a pure sine wave, the accelerating potential on the oscillograph can be adjusted to give a fairly open elliptic trace. If, however, the oscillator output contains harmonics or other undesired frequencies, each of the components will produce its own elliptic trace, and the resulting trace on the oscillograph screen is an ellipse, with a thick outline. If such a trace is obtained, and adjustment of the focusing potentials on the oscillograph fails to sharpen it, then the wave-form of the oscillator is known to contain components of frequency other than the fundamental.

* *Wireless Engineer*, 1933, vol. 10, p. 484.

If a modulated sinusoidal wave of very high frequency be applied to the tube, a thick elliptic trace is obtained, from measurement of which the modulation percentage is easily deducible; for, if the sensitivity of the oscillograph is assumed to be the same for side-bands and carrier frequencies, then it is clear from Fig. 16 that the modulation depth is $\frac{b - a}{b + a} \times 100$ per cent.

Both these applications employ the phenomenon under investigation as its own time-base, use being made of the Hollmann phase effect to obtain the necessary phase-shift, which, at such high frequencies, it would be well-nigh impossible to obtain by any other means.

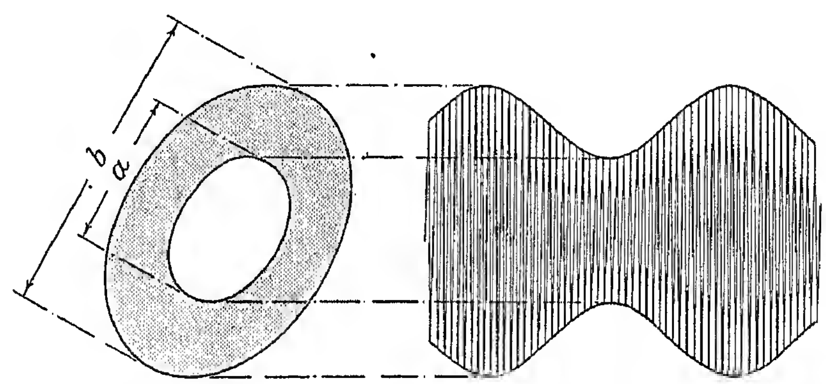


Fig. 16.—Determination of modulation depth.

(5) CONCLUSIONS

When its shortcomings are known and understood, the electron-lens-focused cathode-ray oscillograph should prove itself a most useful instrument at very high frequencies. Its peculiar focusing properties, which ensure a sharp trace at a frequency as high as (and probably much higher than) 1 000 Mc, render possible working at fair precision, provided due allowance be made for the various effects discussed in Section (3) of this paper.

(6) ACKNOWLEDGMENTS

The author wishes gratefully to acknowledge his indebtedness to Mr. L. H. Bedford, of Messrs. A. C. Cossor, Ltd., for the loan of an experimental electron-lens oscillograph, and for much helpful advice on its use. Special thanks are due also to Mr. E. C. S. Megaw, of the Research Laboratories of the General Electric Co., Ltd., for his assistance in the working of the magnetron oscillators, as well as for pointing out the effect of the capacitance of the deflecting plates, discussed in Section (3) of the paper.

The work was carried out in the Electrical Engineering Department of Queen Mary College, University of London, under the guidance of Prof. J. T. MacGregor-Morris, without whose continued interest and help it could not have been done.

APPENDIX I

Nomenclature

$Z_s = R_0 + jL_0\omega$ = series impedance per unit length of line.

$Y = G_0 + jC_0\omega$ = shunt admittance per unit length of line.

$Z_0 = \sqrt{(Z_s/Y)}$ = characteristic impedance of line.

$P_0 = \alpha + j\beta$ = $\sqrt{(Z_sY)}$ = propagation constant of line.

C = terminating capacitance (i.e. capacitance between deflecting plates).

l = length of line.

y = extra length of open-circuited line.

Theory

The two line equations are

$$-\frac{dV}{dx} = Z_sI$$

and

$$-\frac{dI}{dx} = YV$$

which, on solution, give

$$V = V_0 \cosh P_0x + A \sinh P_0x$$

$$I = -\frac{V_0}{Z_0}\sinh P_0x - \frac{A}{Z_0}\cosh P_0x$$

where $V = V_0$ at $x = 0$, and A is a constant.

In arranging the length of the line supplying the deflecting potential to the deflecting plates, it is convenient to have the capacitance of the deflecting plates expressed as an effective extra length of open-circuited line.

For an open-circuited line of length $(l + y)$, $I = 0$ at $x = l + y$, which gives

$$V = V_0 \frac{\cosh P_0(l + y - x)}{\cosh P_0(l + y)} \quad . \quad . \quad . \quad (1)$$

For a line terminated by a capacitance C, $I = jC\omega V$ at $x = l$, which gives

$$V = V_0 \frac{\cosh P_0(l - x) + jC\omega Z_0 \sinh P_0(l - x)}{\cosh P_0l + jC\omega Z_0 \sinh P_0l} \quad (2)$$

Thus the value of V at a point distant y from the end of the open-circuited line must be equal to the value of V at the end of the terminated line, which gives

$$y = -\frac{1}{P_0}\,\text{arc tanh}\,(jZ_0C\omega)$$

For Lecher wires, R_0 and G_0 may be ignored; then Z_0 is purely real, and

$$P_0 = j\beta = j\sqrt{(L_0C_0)} = 2\pi/\lambda$$

and

$$y = \frac{\lambda}{2\pi}\,\text{arc tan}\,(Z_0C\omega) \quad . \quad . \quad . \quad . \quad (3)$$

When R_0 and G_0 are negligible, equation (2) becomes

$$V = V_0 \frac{\cosh 2\pi(l - x)/\lambda + Z_0C\omega \sin 2\pi(l - x)/\lambda}{\cos(2\pi l/\lambda) + Z_0C\omega \sin(2\pi l/\lambda)}$$

and at $x = l$,

$$V_l = \frac{V_0}{\cos(2\pi l/\lambda) + Z_0C\omega \sin(2\pi l/\lambda)} \quad . \quad . \quad (4)$$

For the maximum possible value of V_l,

$$l + y = \frac{n}{2}\lambda$$

which, with equation (3), gives

$$V_{l(max)} = \frac{V_0}{\sqrt{[1 + (Z_0C\omega)^2]}} \quad . \quad . \quad . \quad (5)$$

APPENDIX II

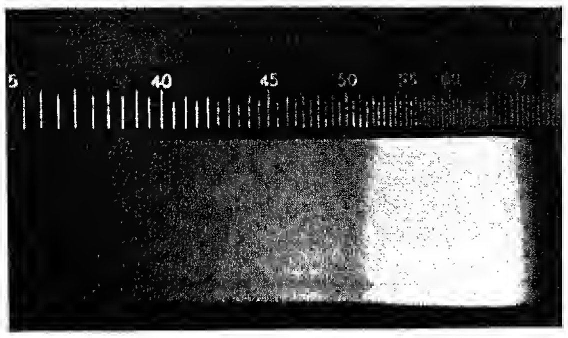
Operating Characteristics of Electron-Lens Tube for Good Focusing Conditions

The following results were obtained for a filament current of 1·2 amps. The meanings of V_1, V_2, etc., are as follows: V_3 = potential of 3rd anode relative to filament; V_2 = potential of 2nd anode relative to filament; V_1 = potential of 1st anode relative to filament; V_c = potential of Wehnelt cylinder relative to filament.

V_3	V_2	V_1	V_c*
volts	volts	volts	volts
1 000	290	140	
	235	165	
	225	215	
1 500	350	255	
	340	270	
	400	335	100
2 200	505	480	150
	510	475	145
	520	440	140
	510	417	135
	530	382	120
	500	347	110
	520	300	100

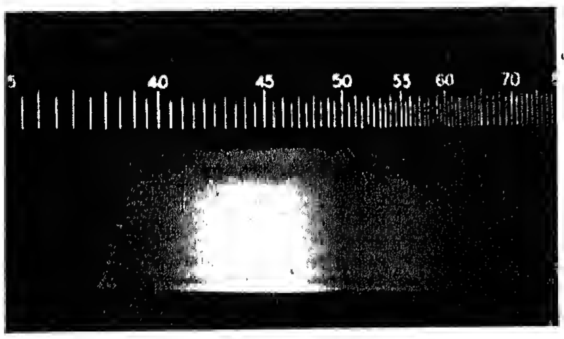
* For the lower values of V_3, V_c was too small to be read on the electrostatic voltmeter used.

[The discussion on this paper will be found on page 25.]



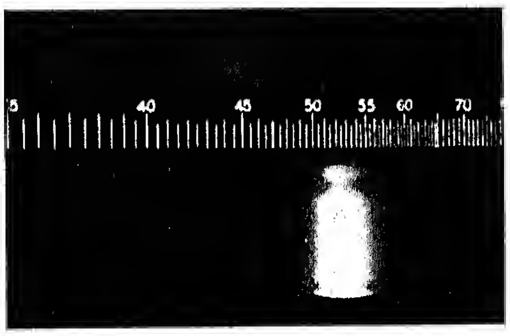
Exposure 1 min.

Fig. 5.—Candle light.



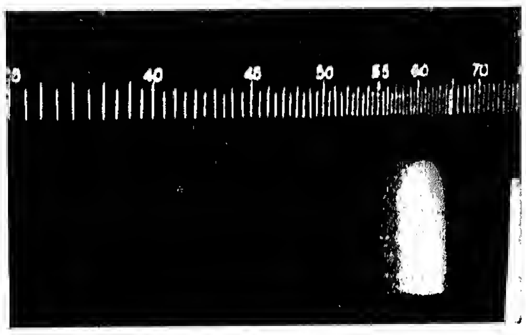
Exposure 5 min.
Current 200 μA.

Fig. 6.—Cadmium tungstate.



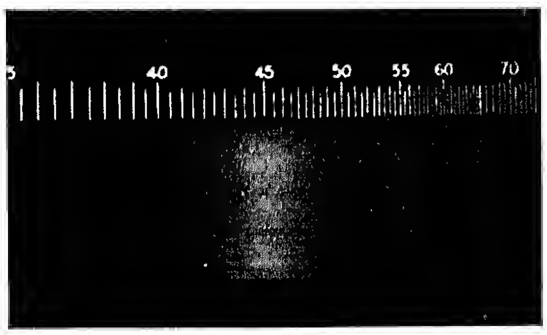
Exposure 4 min.
Current 200 μA.

Fig. 7.—Willemite.



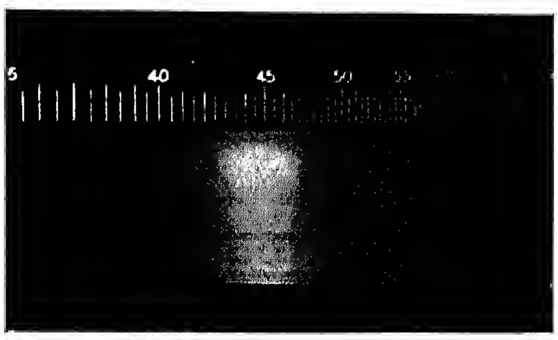
Exposure 3 min.
Current 330 μA.

Fig. 8.—Zinc phosphate.



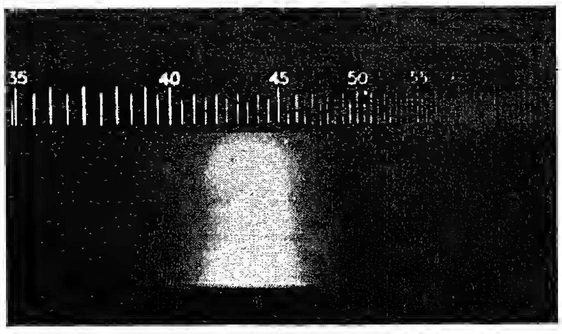
Exposure 2·5 min.
Current 50 μA.

Fig. 9A.—Zinc sulphide U 36.



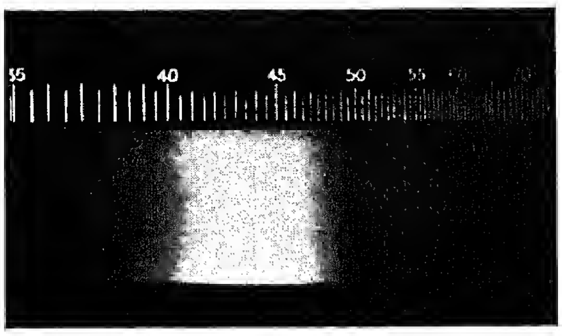
Exposure 40 sec.
Current 200 μA.

Fig. 9B.—Zinc sulphide U 36.



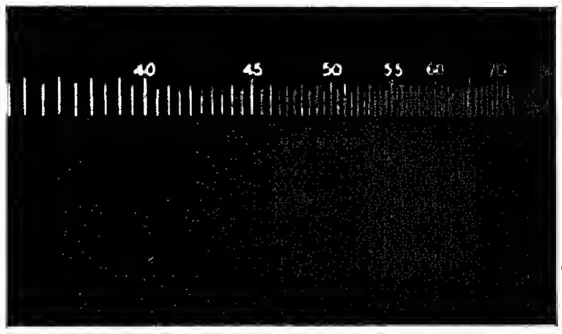
Exposure 45 sec.
Current 50 μA.

Fig. 10A.—Zinc sulphide G 86.



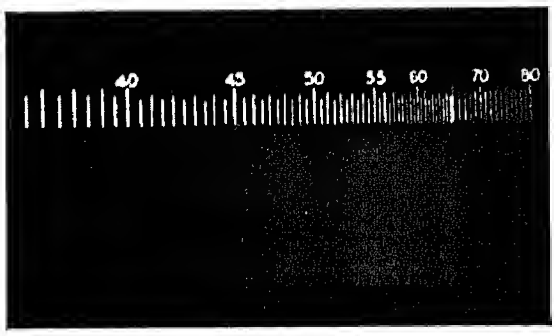
Exposure 30 sec.
Current 150 μA.

Fig. 10B.—Zinc sulphide G 86.



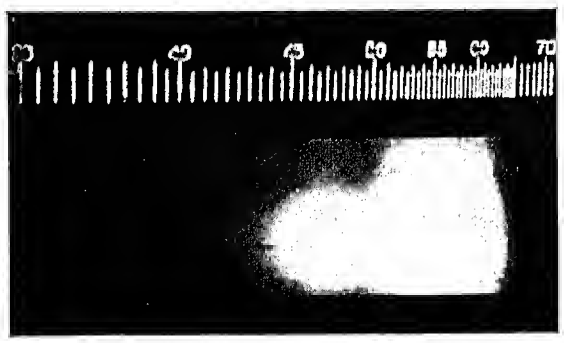
Exposure 1 min.
Current 125 μA.

Fig. 11A.—Zinc sulphide B 7.



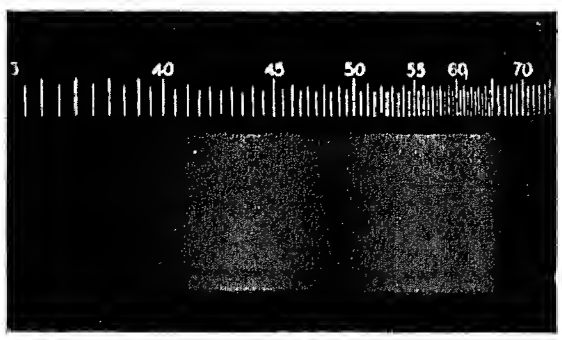
Exposure 1 min.
Current 200 μA.

Fig. 11B.—Zinc sulphide B 7.



Exposure 3 min.
Current 200 μA.

Fig. 12.—Zinc sulphide B 11.

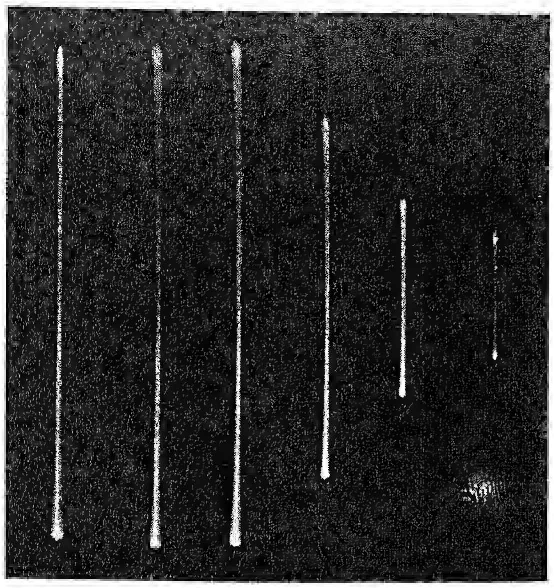


Exposure 3 min.
Current 350 μA.

Fig. 13.—Preparation Z 23 (zinc sulphide and zinc-cadmium sulphide).

Plate 2

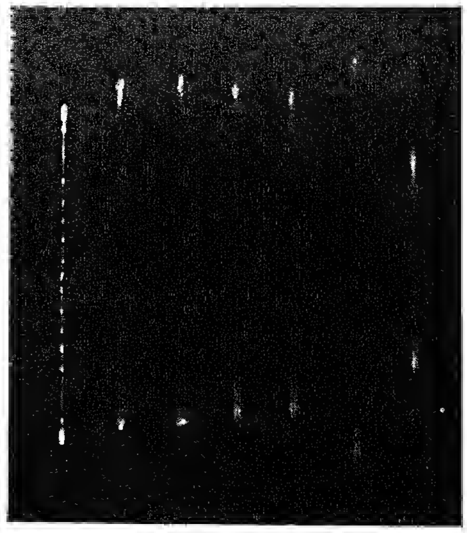
0·26 0·5 1 2 4 8 Mc



$V_3 = 1\,500$ volts.

Fig. 1.—Radio-frequency traces on electron-lens oscillograph.

0·26 0·5 1 2 4 8 Mc
50 cyc.



$V = 600$ volts.

Fig. 2.—Radio-frequency traces on helium-focused oscillograph.

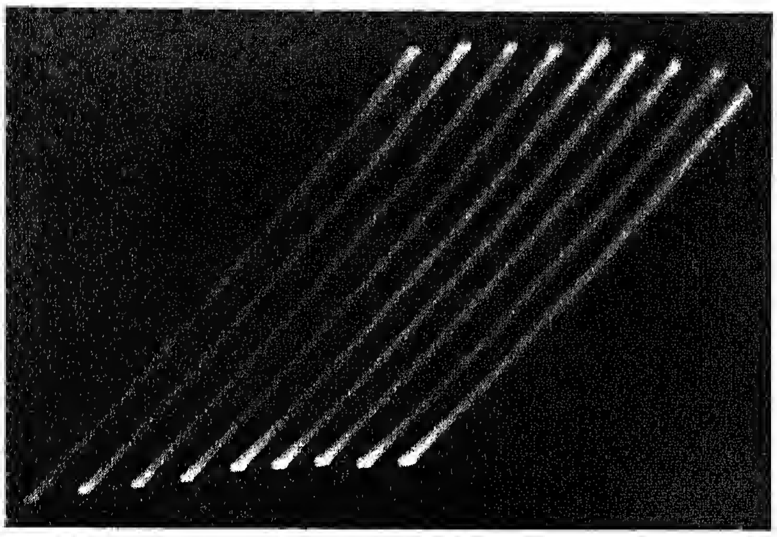
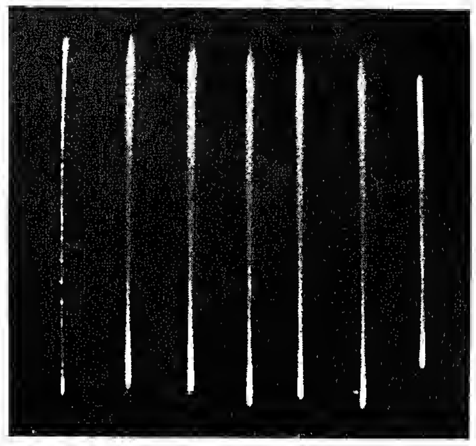


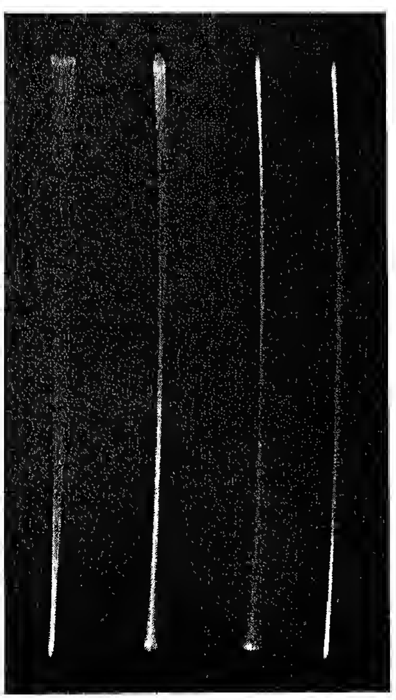
Fig. 6.—Traces showing absence of origin distortion, with electron-lens oscillograph, at 1 Mc. D.C. steps, $\pm$ 30, 60, 90, 120 volts. $V_3 = 1\,500$ volts.

0·26 0·5 1 2 4 8 Mc
50 cyc.



$V = 600$ volts.

Fig. 3.—Radio-frequency traces on argon-focused oscillograph.



(*a*) (*b*) (*c*) (*d*)

Fig. 8.—Optimum focusing at various points in a trace on electron-lens oscillograph.

(*a*) focused at bottom, $V_2 = 375$ volts;
(*b*) focused at middle, $V_2 = 350$ volts;
(*c*) focused at top, $V_2 = 330$ volts;
(*d*) correction applied, $V_2 = 355$ volts. Traces all at 1 Mc. $V_3 = 1\,500$ volts.

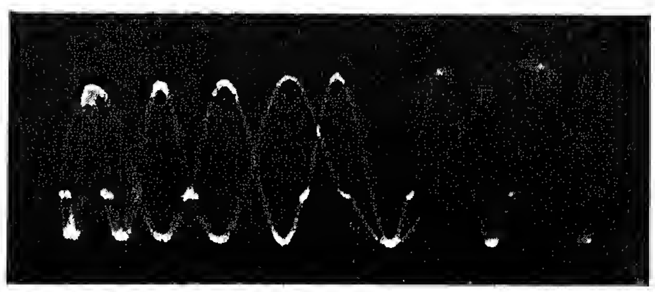


Fig. 9.—Trace on electron-lens oscillograph, at 1 Mc, with time-base, focused at centre of trace.

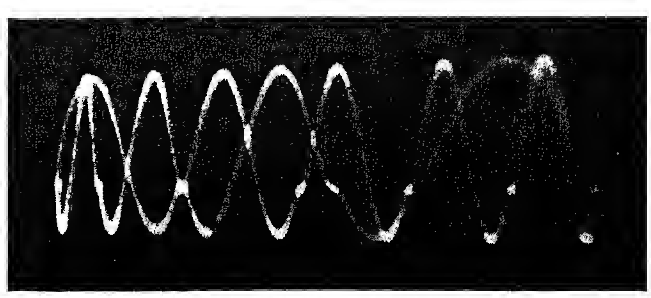
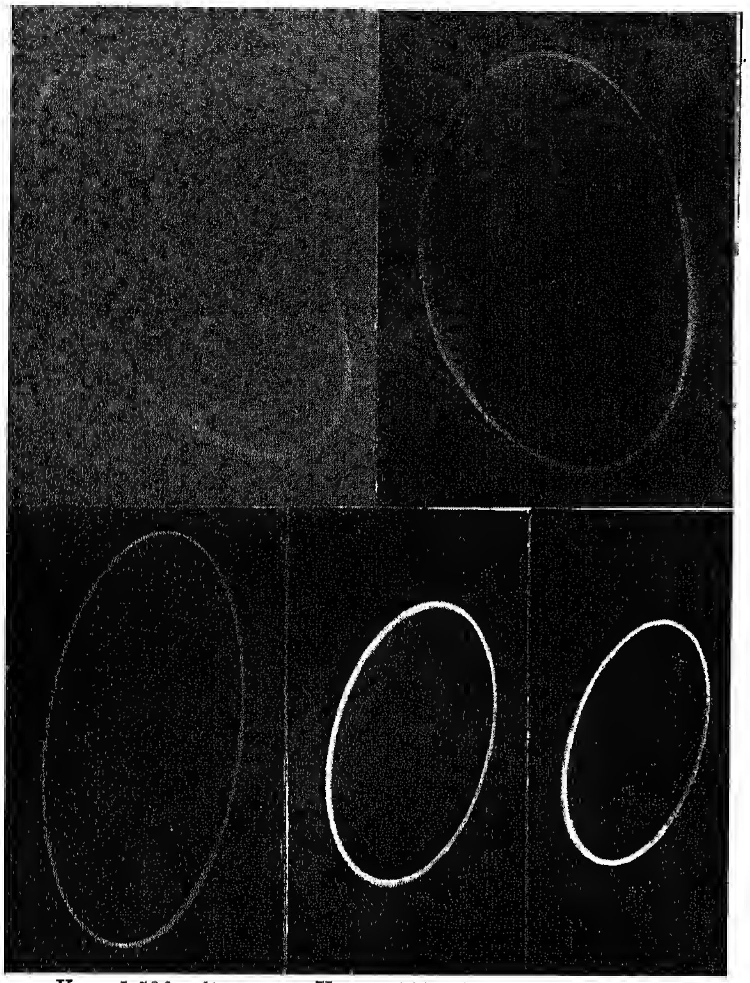


Fig. 10.—As Fig. 9, but with focusing correction applied; operating conditions otherwise unchanged.

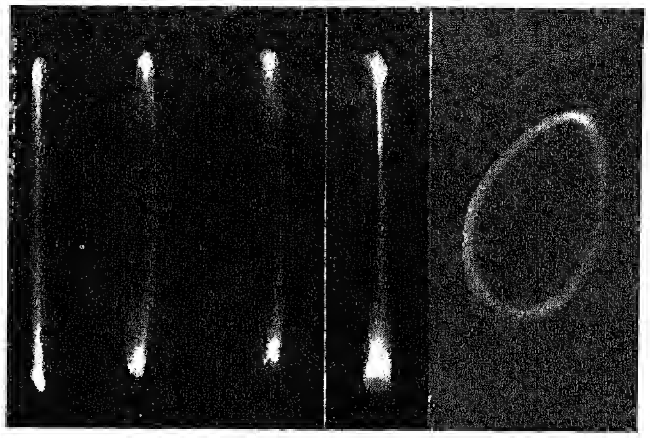
V_3 = 750 volts. V_3 = 1 000 volts.



V_3 = 1 500 volts. V_3 = 2 000 volts. V_3 = 2 500 volts.

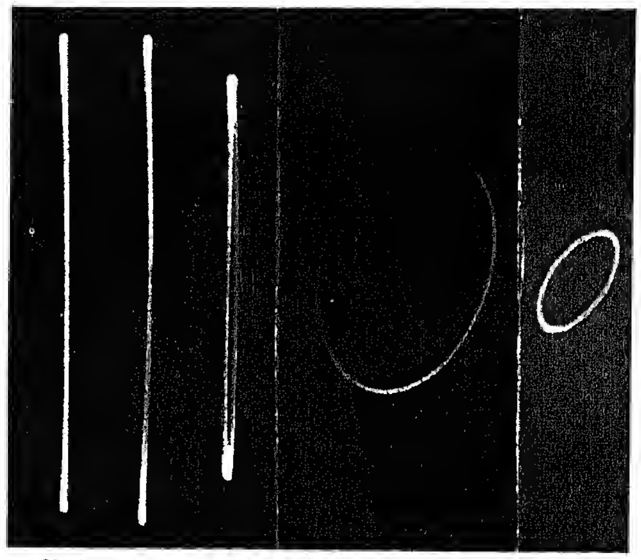
Fig. 11.—Hollmann phase effect at 270 Mc (1·1 m).

83 150 300 441 1 350 Mc



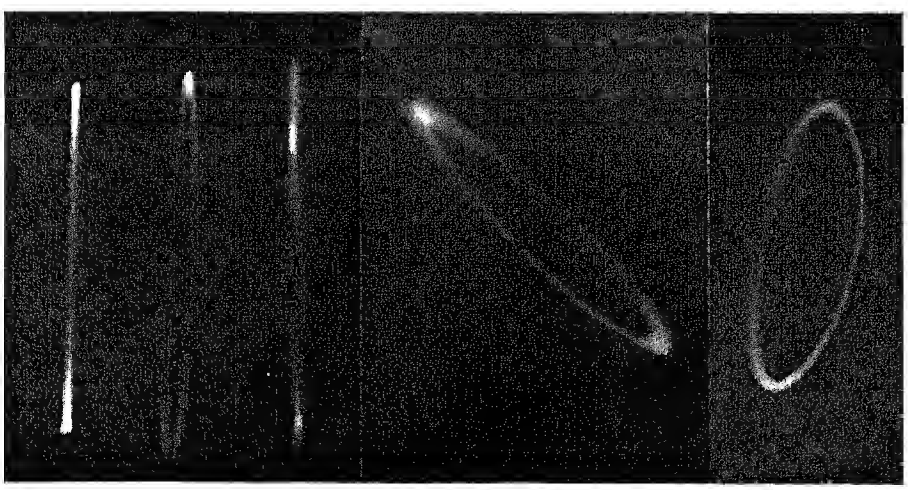
V = 600 volts.

Fig. 12.—Traces on helium-focused oscillograph. (Last trace shows Hollmann phase effect.)



83·4 150 270 500 1 420 Mc

Fig. 14.—Traces on electron-lens oscillograph. (Last two traces show Hollmann phase effect.)



83 150 300 441 1 350 Mc

Fig. 13.—Traces on argon-focused oscillograph. (Last two traces show Hollmann phase effect.)

Plate 4

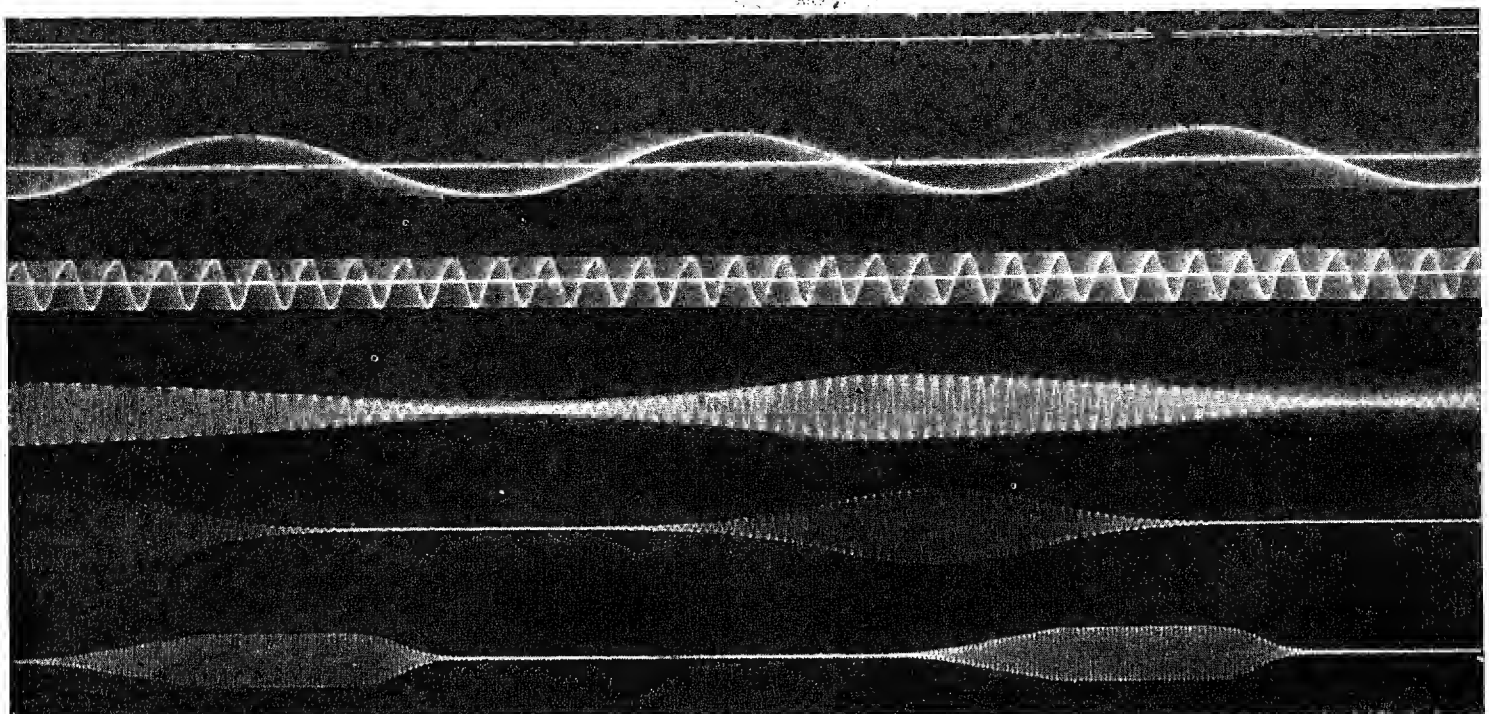


Fig. A.—6-element oscillogram; film speed 97 metres per sec.

Fig. B.—Oscillogram of wave-form best suited to study of phosphorescent effect. Fundamental frequency 100 kc.

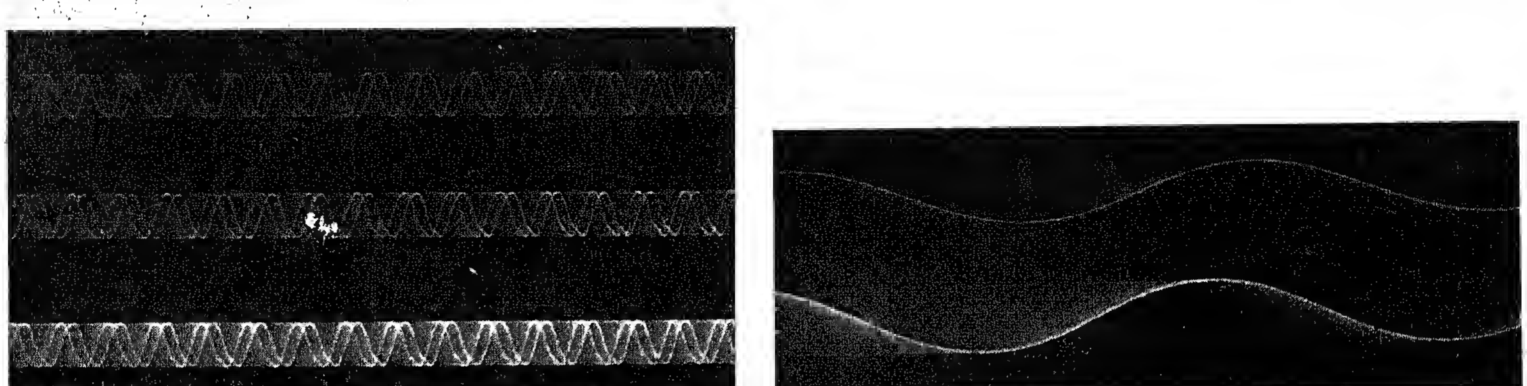


Fig. C.—Effect of variation of beam current.

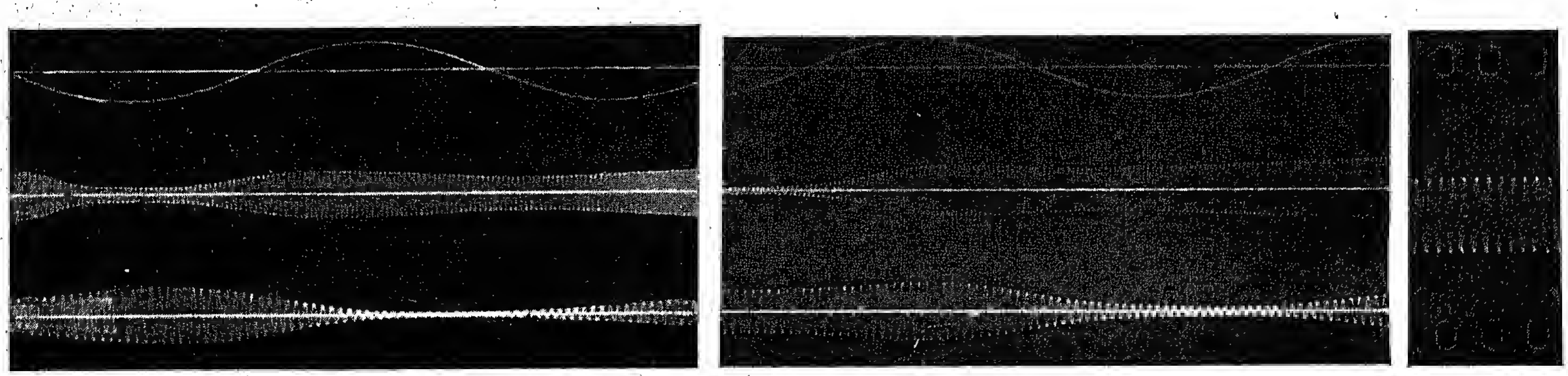


Fig. D.—Effect of using photographic emulsions whose maximum sensitivity lies in different parts of the spectrum.

(*a*) Wide-latitude emulsion; 2 kc, 200 kc, 100 kc.
(*b*) Emulsion with cut-off in the green; 2 kc, 200 kc, 100 kc.
(*c*) Ultra-blue-sensitive emulsion; 50 kc.

DISCUSSION BEFORE THE WIRELESS SECTION, 4TH MARCH, 1936, ON THE PAPERS BY DR. LEVY AND MR. WEST (SEE PAGE 11) AND MR. PIGGOTT (SEE PAGE 20)

Mr. L. H. Bedford: It is unfortunate that in a communication of such importance the authors have neglected an opportunity of assisting the art in the matter of terminology, in that both the terms "fluorescence" and "phosphorescence" are employed. On purely physical grounds there is no room in the language for both of these terms, since there seems to be an absence of any sharp dividing line between the phenomena implied. On any ordinary physical conception of the process of fluorescence, we must assume that the light is emitted when the material passes from a higher to a lower energy level. It is stimulated to a high energy level by electron bombardment, and the light emission takes place during the restoration process; this may take a long or a short time, but it can hardly take no time. Therefore, if the term "fluorescence" is restricted to mean the "instantaneous" light response, fluorescence will not exist; and if it is restricted to imply the "substantially instantaneous" response, then the term is without meaning.

According to our measurements, the response of a fluorescent material can be expressed in terms of one or more time-constants. The response of materials such as calcium tungstate or zinc phosphate is characterized by a single time-constant, expressing the fact that on the cessation of electron bombardment the light response falls exponentially. Materials of the zinc-sulphide class show a much more complicated response which, however, can with fair approximation be resolved into a number of independent light-responses each having associated with it a specific time-constant and spectral distribution. The zinc sulphides generally are characterized by having one response component with an exceedingly short time-constant, namely a small fraction of a microsecond, and another response of much lower intensity having a time-constant of the order of seconds. There are also, however, components with intermediate values of time-constants, but the characteristic of the more useful zinc sulphides is that the shortest time-constant component predominates very strongly in intensity. This type of complex response would appear to defeat completely any attempt to make a dividing line between "fluorescence" and "phosphorescence," and I consider that the subject would gain in clarity if one of these terms were dropped.

Mr. E. C. S. Megaw: I shall confine my remarks to the paper by Mr. Piggott.

In the first place I should like to ask for details of the technical difficulties which I know must have been involved in producing oscillograms at frequencies up to nearly 1 500 Mc, and of the ways in which those difficulties have been overcome.

The most outstanding point which emerges from the paper is the fact that the gas-focused oscillograph, which has excellent focusing properties at low frequencies, rapidly loses its focus as the frequency is increased into the region of hundreds of kilocycles, has fairly bad focusing characteristics throughout the normal radio-frequency range, and then recovers in the region of tens or hundreds of megacycles. The author makes no attempt to explain this effect, which may be thought of in the following way. At very low frequencies the positive ions, which are responsible for holding the beam together and giving the focus, are produced wherever the beam is at any particular moment. At extremely high frequencies the positive ions are practically unable to follow the motion of the beam, and the result is a diluted positive space-charge through the whole region in which the beam is moving, from which we obtain a certain amount of focusing effect. At the intermediate frequencies, on the other hand, the positive ions are able to follow the motion of the beam to some extent, but not completely, so that as a rule they are in the wrong place and tend to drag the beam out rather than to compress its cross-section. I should like the author's opinion of this attempt at an explanation.

I am particularly interested in his reference to the use of the de-phasing effect which occurs at extremely high frequencies, and which is due simply to the appreciable time taken by the electrons in passing from one pair of deflecting plates to the second, as a method of examining the properties of very high-frequency oscillators. Such methods are indeed very badly wanted, and promise to be a very useful tool in examining modulation problems at frequencies of the order of megacycles.

I should like to comment on his method of measuring modulation by means of the thickened ellipse which is obtained on the fluorescent screen of the oscillograph from a modulated signal. One of the difficulties experienced in modulating extremely high-frequency oscillators is that of getting either pure amplitude modulation or pure frequency modulation, and in particular of getting amplitude without frequency modulation. If both are present it is not possible to separate their effects simply by looking at the thickened ellipse. Several modifications suggest themselves; such as, for instance, taking a cinema film of the thickened ellipse and examining each frame and seeing whether the ellipse remains the same shape and merely alters its size (indicating pure amplitude modulation), or whether both shape and size vary (indicating frequency as well as amplitude modulation).

It is clear that the author has indicated two ways in which the phase-lag effect due to electron transit time may be of great service in studying the properties of very high-frequency oscillators.

His results are of particular interest to the concern with which I am associated, because 2 years ago we used an ordinary commercial oscillograph to obtain modulation diagrams by putting the radio-frequency carrier direct on one pair of plates and the audio-frequency on the other. We obtained such diagrams at frequencies up to about 300 Mc with tolerably good focusing, using a gas-focused tube. Normal methods of measuring modulation with a cathode-ray tube are apparently practicable, at least for approximate purposes. The paper indicates that in the future the degree of approximation may be very considerably improved

when we understand the nature of the phenomena which occur at such high frequencies.

Mr. T. C. Macnamara: There is one question which I should like to put to Messrs. Levy and West. In view of the fact that such considerable brilliance of image can be produced on the large tube, and in view of the statement in the paper that certain fluorescent materials do not seem to saturate easily, is it inconceivable that a very much brighter image might be produced which could be optically projected to produce a larger picture? I do not know whether a screen would be capable of standing up for any length of time under a much heavier bombardment, but it seems an interesting idea.

The authors point out that rather more light is given out from the back of the screen than from the front, particularly if the front is backed with a white reflector such as a piece of paper. Would it be possible to consider operating with the screen at an angle to the scanning beam, observing the same side as one is scanning, so as to make the very best use of the available light? It would be necessary, of course, to compensate for keystone effect, etc., but it seems that there would be a considerable gain in illumination.

Mr. Piggott's paper is of particular interest to me because I can appreciate from it the advantages which the electron-lens-focused tube has over the gas-focused tube. One of the most serious troubles associated with the taking of oscillograph pictures with the gas-focused tube was the bugbear of origin distortion. I found that if by means of a magnet one deflected the spot from the point at which it came to rest when there was no bias on the deflecting plates, and brought it back to the centre of the tube with electrostatic bias, the area of origin distortion could be removed right off the end of the tube, and one could proceed in a straightforward way to look at pictures. The only trouble was that in those circumstances the deflection of the spot was not always the same for a given positive as for a given negative excursion, so that one tended to get images which were distorted. Apparently this disadvantage is quite overcome with the electron-lens-focused tube.

Being able to observe fairly clearly traces due to frequencies of the order of 100 to 1 000 kc is also a very great advantage, because in investigating modulation problems it is interesting to see a trace due to the high-frequency voltage. With the gas-focused tube it was almost impossible to do this, as the image was always rather indistinctly defined and the extent of it could not be observed very well.

Mr. R. A. Watson Watt: Mr. Piggott talks about certain phenomena which he calls "Hollmann effects." I suggest that if we are to have proper names attached to these effects the appropriate proper name in this case is that of Prof. MacGregor-Morris, because the essence of the Hollmann effect was specially dealt with by him in the discussion on a paper by R. A. Watson Watt and J. F. Herd.*

Prof. J. T. MacGregor-Morris: I do not think that any credit is due to me in regard to the subject mentioned by Mr. Watson Watt. I believe, however, that he and the late Mr. Herd and Mr. Mines were early in the field, and therefore their names might have claims to be attached to the effect in question.

There are a few points in the paper by Messrs. Levy and West to which I desire to refer. First, from Fig. 1 it looks as though it might be worth while bearing in mind that the candle-power is, broadly speaking, proportional to the square of the voltage.

Next I should like to ask how far the burning by cathode-ray bombardment of fluorescent materials has been overcome. Is it possible to reduce the burning by having a good thermal conductor behind the fluorescent material? If so, then the method of viewing the front of the screen instead of the back would probably be the better.

In Section 5(*c*), should not the results be expressed in "international candles"?

Dealing with the illumination produced on the fluorescent screen, if one defocuses the spot so that it covers a certain patch, and alternatively focuses the spot down to a very small, sharp point, making it rapidly trace and retrace over the patch, as in television methods, is the effective illumination produced by the two processes the same? One can imagine that if one gives a sudden excitation to the fluorescent screen it trembles into light, and that light continues while one is busy lighting another piece of the screen, until one comes back and gives the original small spot a fresh excitation. Is it possible to get a greater total lumen-seconds from the intermittent method of lighting as compared with the steady-beam method?

I have always had some difficulty in distinguishing clearly between phosphorescence and fluorescence. If one takes a time curve of the growth of the illumination of a fluorescent screen for a cathode-ray beam steadily impinging on a certain point on it, how does the illumination increase? In the paper I notice that the phrase "almost instantaneous" is used. How long does the illumination take to grow to its maximum value? Also, how does the illumination decay? I think that, if we knew these laws completely, for various preparations, we might be able to progress still further.

Turning to the paper by Mr. Piggott, in the second paragraph of Section (4) he says "The Hollmann phase effect can be overcome by a special tube produced by Von Ardenne." It might be of interest to many of us if the author would outline the method that was used to overcome that effect.

There is one suggestion that I should like to make. If one has to work with an oscillograph at a constant but very high frequency, there is a method which might be used of subdividing the plate into sections and obtaining increased deflection. As the wave is alternating in character, the electrons proceeding along between the plates are first deflected between one pair of plates and then further deflected between the next pair as soon as the polarity is reversed. The method is not as good as that of the Zworykin electron multiplier, which gives a successive multiplication by a factor of, say, 5; the device I have mentioned would add only in steps of $1 \times 2 \times 3 \times 4$, etc.

Mr. L. C. Jesty: The two sets of curves given in the paper by Messrs. Levy and West, taken with the flicker-photometer and with the photocell respectively, are an

* *Journal I.E.E.*, 1926, vol. 64, p. 611.

object-lesson to all concerned in the correct method of obtaining the true values of brightness from coloured sources. The photocell can give us relative values, but the " true " value of brightness which it gives is, as we can see from these curves, most misleading.

My criticisms are mainly confined to the method of measurement of these curves. We have been making some measurements of a nature similar to those published here, and have found that two effects are very important in controlling the type of fluorescence obtained in television tubes. The first effect is the velocity of the spot, assuming that it is focused to a definite size. If the velocity of the spot varies as the spot travels over a given area on the screen, the illumination produced will vary accordingly; in general, the slower the speed of the spot the lower the illumination produced. In particular this is noticeable in changing over from a 240-line scan to a 400-line scan. I suggest, therefore, that the last method outlined in the paper introduces the possibility of grave errors, and this must be taken into account in the interpretation of the curvature in these diagrams.

Secondly, with regard to Figs. 2 and 3, where in one case candle-power is plotted against current for a constant voltage, and in the other case candle-power is plotted against voltage for constant current; in the variation of both these variables, voltage and current, it is almost impossible to obtain a constant size of spot. I have yet to see the cathode-ray tube which will give, say, a 1-mm spot at all intensities of current and voltage. As these quantities are varied, therefore, the current density in the beam will also vary, and this effect will naturally produce a variation in the light output owing to uncontrolled variation in the method of excitation.

The last question on which I wish to touch is that of uniformity of screen construction. We know from bitter experience that, even using the same material and the same binder, unless very great control is exercised in making the screen, variations at least as great as 2 to 1 can occur in the ultimate efficiency. It would be of interest to know whether any control was exercised in making these screens, or alternatively whether a number were used and the average values taken in giving the results.

Dr. D. H. Black: I propose to confine my remarks to the paper by Messrs. Levy and West, and to ask them whether they can throw any light on a rather puzzling phenomenon which we encountered some time ago in our development of cathode-ray tubes. We found on some screens a mysterious black line when the whole screen was fluorescent. At first we thought that the screen material had been burned, but closer investigation showed that this was not the case, and we were at a loss to understand what it was until one of my colleagues made the suggestion that it was possibly due to bombardment by negative ions. I pooh-poohed the idea to start with, but on looking into the matter we found that all the evidence pointed to this, and some time later we discovered that Von Ardenne had published a paper to the same effect.

This black line shows up particularly when one is working with combined electromagnetic and electrostatic deflection. It can be shown quite easily that, if one is applying electrostatic deflection to negative ions, the deflection obtained by applying a certain potential to the plates is exactly the same as would be obtained for electrons; but if one is using magnetic deflection the magnitude of the deflection depends upon the ratio of the charge to the mass of the electron or ion concerned; and therefore, as the lightest ion is some 1 800 times heavier than an electron, the deflection caused by the magnetic field is very small, and we get our straight line across the screen. We tried to determine the atomic weight of this ion by applying constant magnetic fields of known strength which deflected the electron beam right off the screen and displaced this line by a small amount, and then finding what magnetic field was necessary to displace the electron beam by exactly the same amount. The experiments were naturally somewhat inaccurate, but what evidence we did get suggested that the ions were probably due to oxygen.

To me this result is rather puzzling, because we know that fluorescent screens have been used for years now to detect positive ions in the shape of α-particles and high-speed protons, and yet no signs have ever been detected, by us at any rate, of fluorescence caused by bombardment by these negative ions. I should like to ask the authors whether they can offer any explanation, first of all, of why we perceive no fluorescence from these negative ions; and, secondly, of how it is that they manage to " poison " the screen in the manner that they do.

Mr. O. S. Puckle: A focus-correcting system such as that used by Mr. Piggott with a high-vacuum oscillograph tube and with the source under examination unbalanced, was tried some time ago, but unfortunately it was not very successful. In this connection I notice that in the author's photographs, although the focus is improved, it is not quite satisfactory all over the screen. In Fig. 7 the choke might with advantage be replaced by a resistance, except perhaps when the circuit is to be used at ultra-high frequencies. The use of composition resistances of the type employed in commercial radio receivers should be avoided at ultra-high frequencies on account of the Boella effect.*

Another method of avoiding the defocusing effect is to use an additional valve as a phase-changing valve and so to convert an unbalanced into a balanced source. I have been able to make this arrangement function successfully over quite a large frequency range. It is of interest to note in this connection that the use of balanced deflection with a hard cathode-ray tube does not, as is perhaps generally believed, entirely remove the defocusing effect; in fact, if an extremely large deflection is used, it is possible still to have defocusing at the edges of the screen if either the beam or the deflecting field is not homogeneous.

With regard to the lack of focus of gas-filled tubes at intermediate frequencies, and to the fact that they regain their focusing property later (i.e. at still higher frequencies), I consider that the *modus operandi* is somewhat as follows: When a series of sine waves appear on the screen in such large numbers that they are packed closely together, the ionization due to the passage of the beam along the oscillograph tube when delineating one

* *Wireless Engineer*, 1935, vol. 12, pp. 291, 303.

sine wave assists to a certain extent in keeping the beam focused over the length of the next sine wave, and so on. Again, if the rate of repetition of the passage of the beam over any particular path is so high that the path has not sufficient time to become totally de-ionized between traversals, the amount of ionization will build up till the increment of ionization is equal to the decrement over a period of time. Thus, during the small period of time when the beam is on any particular part of the screen, a small increment of ionization is provided and the ionization falls away while the beam is traversing the rest of its path, so that a certain average amount of ionization is present. Whether that amount of ionization is sufficient to provide a good focus depends on a number of factors.

I hold the very definite opinion that the only satisfactory method of referring to the limiting focus conditions for gas-focused tubes is in terms of writing-speed and not in terms of frequency. The frequency at which a gas-focused tube begins to fail is dependent upon the amplitude of the sweep in both the horizontal and the vertical directions, and also upon the distance between adjacent portions of the image. The only term which includes all these components is the "writing-speed," usually expressed in metres or kilometres per second at the surface of the screen. If the oscillograph is always used with a fixed-focus camera the writing-speed at the surface of the photographic plate may be employed if found convenient. For the above reason I consider that Figs. 2 and 3 (see Plate 2) of the paper, purporting to show the focusing action of gas tubes over a large range of frequencies, do not depict the true situation since the beam continually covers the same path in the form of a straight line, and, therefore the writing-speed has the minimum value which it is possible to obtain with that particular time of traverse, if the flyback is neglected.

The method of regarding the deflecting plates of a cathode-ray tube as an additional line of determinable length, when the tube is used at extremely high frequencies, is a very interesting one, but it would appear that in practice the mathematical difficulties are greatly reduced by using cathode-ray tubes in which the deflector-plate connections are brought out at the side. In addition, the ultra-high-frequency losses will be less in a tube of this type and the design of the necessary feeder line is simplified.

It is of very great interest to note that Mr. Piggott has managed to make use of the Hollmann effect, which has always been regarded as a disadvantage.

Mr. W. E. Benham: I should like to inquire whether Messrs. Levy and West have observed voltage saturation of the screen in addition to current saturation.

In connection with the curves shown in Figs. 1, 2, and 3, I should like to ask the size of the raster used in making the experiments.

The question of heat treatment is of interest to those who are using the substances in cathode-ray manufacture. The information of most value would seem to me to be the temperature to which it is safe to take the fluorescent material during glass-bake, and the permissible time that the material may be maintained at the maximum temperature without altering its properties. The effect of different binding materials is also of importance. The authors indicate in Section (7) that an excess of silicate can result in degradation of the luminescent qualities. If, however, some excess is not present, there is danger of the powder being shaken off. What is wanted, therefore, is a binding medium which can be applied in excess without fear of harming the powders.

My next point is concerned with the difference in fluorescent response under ultra-violet ray and electron bombardment. It seems that no satisfactory theory of fluorescence has been proposed. An interesting point to note at the outset is the great difference in the exciting energy required in the case of electron bombardment (say, several hundred volts) as compared with ultra-violet bombardment (say, 10 equivalent volts).

Dealing now with Mr. Piggott's paper, our experiments tend to confirm that negative ions are produced in a cathode-ray tube and that these ions are probably oxygen rather than hydrogen ions. Very little is known about negative ions, but it is reasonably certain that they arise at very low voltages. The suggestion that the ions arise at the surface of the cathode or very near, is borne out by the fact that the electrostatic deflection of the ions is equal to that of the electrons as far as can be observed. The ultimate origin of the ions may be found in the electrolysis of the cathode coating, according to a theory held by Mr. Bedford and myself some years back. In regard to positive-ion focusing of the cathode-ray beam, it would seem probable that the focusing is no longer efficient when the electron beam is deflected by an e.m.f. of period comparable with the de-ionization time.

Mr. William Joseph Scott: I should like to refer to one point in connection with the paper by Messrs. Levy and West, namely the effect of temperature on the light output of fluorescent substances.

We have observed that the luminous efficiency of certain zinc-cadmium-sulphide compounds falls off rapidly at temperatures above some 200° C. It is obvious that the intense impinging of a cathode-ray beam will increase the surface temperature of the luminescent powder at the cathode spot, perhaps to such a degree that the temperature effect itself may be the main cause of the fall in screen luminous efficiency with high beam current-densities or voltages. Also the actual temperature of the screen as a whole must make a good deal of difference to the light output. Have the authors any figures in regard to this? Again, what is the effect of exhaust heat treatment such as baking at 400° C. or higher in the presence of different binders, and what binders are available for use with these substances?

Mr. John Charles Wilson (Manchester): I should like to endorse the remarks of Mr. Bedford with regard to phosphorescence and fluorescence. I have been following to some extent the idea put forward by Prof. Baly* regarding the mechanism by which phosphorescence and fluorescence are distinguished. He took what I think is an almost exact parallel to the case which we have been shown where there are two distinct forms of luminescence differing in lag; he took the case of a phosphor in which the excitation of each molecule or aggregate was quite instantaneous, and postulated that the phosphor aggregate lost its energy in two steps, the

* Report of the British Association, 1928, p. 35.

first occurring immediately upon excitation and the second after an indefinite interval. During this interval the aggregate is in a meta-stable condition and the final loss of energy is analogous to that occurring when a radium atom disintegrates; decay of afterglow therefore follows an exponential law corresponding more or less with that of the loss of weight of radium. I imagine that he envisaged a similar result to that which Messrs. Levy and West demonstrated with the electro-cardiograph tube. The lag of the greenish component would then be exponential.

Their curves showing the points of saturation of these screens are very interesting. We find that the binder is a controlling factor in deciding whether saturation occurs. Von Ardenne has published a curve* showing a saturation effect associated with the use of a binding material (potassium silicate), and alongside it is shown a curve of a similar phosphor in which no saturation occurred within the extent of his results—though it may have occurred farther on—and in which the screen was burned (*eingesintert*) into the glass.

Messrs. Levy and West describe the caesium cell as having a high sensitivity to the blue end of the spectrum. I should like to check this point, because it seems a little unusual.

Finally, I would point out that, in addition to de-activators of the type of nickel, other de-activators have been described, such as iron, cobalt, and chromium.† For some purposes, and particularly television purposes, infra-red killing has been used. This is very effective with screens excited by ultra-violet and visible light but not so much so in the case of electronically-excited phosphors. I should welcome some information on this point.

(*Communicated*) With regard to Fig. 2 in the paper by Messrs. Levy and West, I should like to point out that none of the curves appears to pass through the origin; this implies a " current threshold " which has not been noticed by any other workers so far as I am aware. As the matter is of considerable importance I should like to draw the authors' attention to it and to ask them whether they have an explanation.

Mr. D. A. Bell: It seems to me that we still lack an explanation of the return to focus of the gas-focused tube at very high frequencies. Surely the focusing is due rather to a difference in concentration of positive ions between the region occupied by the electron beam and the surrounding space than to the mere presence of these positive ions. In that case, the fact that at high frequencies there may be positive ions throughout the region will not help us. Has this increased concentration some effect on the de-ionizing time, i.e. is there a rapid fluctuation about a high mean level of ionization at very high frequencies, compared with a slower return to zero ionization at lower frequencies? The other question on which I am not clear is whether the gas-focusing occurs entirely between the deflecting electrodes or right up to the moment of impact with the screen. In the latter case I am not sure that we have any justification for saying that the positive ions move with the electron beam.

* M. Von Ardenne: " The Cathode-Ray Tube " (Julius Springer, Berlin, 1933), p. 86.
† J. W. Mellor: " Treatise on Chemistry," vol. 4, p. 592.

Mr. L. Samphier (*communicated*): I propose to confine my remarks to the paper by Messrs. Levy and West.

Can the authors complete the series of curves shown in Figs. 1 and 2 by a set showing variation of intensity under working conditions, i.e. the variation with gun voltage when the spot is kept in sharp focus for any given potential? I presume that the curves in Fig. 1 do not necessarily fulfil these conditions.

Can the authors supply any data concerning the actinic value of the light emitted by screens specially prepared for photographic work? These screens, used in conjunction with films or papers coated with the special emulsions now available, prove satisfactory for a wide range of speeds. Can any improvement in the steepness of response be effected? In photography by the single-sweep method, trouble is often caused by illumination, due to stray bombardment of the screen, giving rise to fogging of the film. Special methods have sometimes to be used to prevent this.

Are there available any methods for controlling the duration of afterglow? In the use of screens giving a red response with a long afterglow, I have formed the impression that the obtaining of a sharp focus is not so easy as with screens giving a blue fluorescence. Can the authors give any confirmation of this impression?

Is there any variation in the life of screens composed of different materials?

Mr. G. A. Whipple (*communicated*): I have one major criticism of the paper by Messrs. Levy and West. The title states that it deals with " Fluorescent Screens for Cathode-Ray Tubes for Television and other purposes." My criticism lies in the fact that the " other purposes " are crowded into so small a space as Section (6) of the paper.

I belong to the small minority who use cathode-ray oscillographs as oscillographs and not as cyclographs or picture-reproducers. Until recently, the cold-cathode, continuously evacuated oscillograph was the only instrument capable of recording phenomena of very short duration. The advent, however, of the " hard " electrostatically focused tube, and the production, largely by the authors, of fluorescent materials such as those described in the paper, have brought forward the hot-cathode sealed-off tube as a precision instrument, capable of relatively high writing-speeds. It is frequently necessary, however, to use the tubes as oscillographs as opposed to cyclographs; in other words, to use the movement of the recording medium to impress motion proportional to time. It is in this case that the part played by phosphorescence as opposed to fluorescence becomes of great importance in the selection of a screen for the recording tube.

A 6-element oscillograph has been recently constructed by the Cambridge Instrument Co., in collaboration with the Electrical Research Association, using " hard " tubes, running at 5 000 volts accelerating potential. Light from the fluorescent screens is transmitted to a moving photographic film by means of short focal-length lenses having an aperture ratio of 1·4 and giving a 10:1 reduction. The peripheral speed of the drum carrying the film is approximately 100 metres per second or 10 microseconds per mm. It is therefore clear that if the main-trace width, due to the fluorescent effect, is

0·1 mm, then, owing to the rapid lateral movement of the film, the phosphorescent effect has only to last 1 microsecond to double the trace width during its persistence. This effect is shown clearly in Fig. A (see Plate 4, facing page 25) where the trailing effect caused by the phosphorescence is noticeable on all records, and badly blurs the 20-kc trace. The screens of the tubes used are coated with a zinc-sulphide preparation of the type described in the paper. A modulated high-frequency oscillation is found to be the most suitable wave-form for checking the time-constant of the phosphorescent effect. In particular, the wave-form shown in Fig. B is excellent, since the trail from alternate high-frequency peaks is clearly shown.

It would be very helpful if the authors could give more data as to the relationship of fluorescence to phosphorescence. The aim must clearly be to attain the highest possible ratio of actinic fluorescence to phosphorescence, in order that a clean record may be obtained. I should like to ask how this ratio varies—if it varies at all—with accelerating potential, and with beam current. Fig. C(*a*) shows three traces of a frequency of 20 kc taken with varying beam current. The phosphorescent effect here, whilst varying with the fluorescence, does not appear to do so directly.

The phosphorescent effect is presumably of the indirectly-excited type, since the light emitted appears to be of greater wavelength than that of the fluorescence. This is shown by Fig. D, in which (*a*) and (*b*) are records obtained under similar conditions; (*b*), however, being taken on an emulsion having a lower response in the green part of the spectrum. In the same figure, (*c*) shows a portion of a trace taken on an ultra-blue-sensitive emulsion. No trailing effect, due to phosphorescence, is visible, but the emulsion is too "contrasty," and is objectionable in use as it is prone to electrostatic troubles in winding and unwinding of the film. If the authors could add to their paper further spectrographs giving some accurate indication of the wave band occupied by the phosphorescence and fluorescence and their relative intensity levels, it might be possible to eliminate this effect entirely by the suitable choice of emulsions, or the use of filters, rather than by the employment of "killers" which lower the fluorescent efficiency and consequently the writing-speed of the tube.

I should like to suggest that the high-speed camera is the authors' best method of measurement of the time-constants of decay of both fluorescence and phosphorescence, and it is only through a desire to help them in the production of screens for oscillography that I put forward these records (Figs. A, B, C, D) showing the serious results of the phosphorescent effect, even when the time-constant is as short as 1 microsecond.

I should like, in conclusion, to express my thanks to Dr. Baines and Mr. Woosley, of Messrs. Ilford, Ltd., and to Mr. L. H. Bedford, of Messrs. A. C. Cossor, Ltd., for their kind collaboration in this work.

Dr. L. Levy and **Mr. D. W. West** (*in reply*): We are not quite in agreement with Mr. Bedford regarding the points he has raised on the question of the definitions of phosphorescence and fluorescence. Fluorescence is usually regarded as essentially different from phosphorescence inasmuch as fluorescence is believed to be a change occurring in the molecule itself, whereas phosphorescence is believed to be due to the transit of electrons from one molecule to another. Fluorescence is excited apparently instantaneously whereas phosphorescence frequently builds up quite gradually, as can readily be observed by exposing luminescent zinc sulphide to ultra-violet radiation. If, for example, a zinc-sulphide preparation containing copper as phosphorogen is exposed to ultra-violet light, the fluorescence first obtained is bluish-green. As the phosphorescence builds up, this colour changes to a yellowish-green and increases in intensity for about 1 minute, the exact period depending upon the nature of the preparation.

Another observation which leads us to maintain that fluorescence and phosphorescence are essentially different, and not merely the same phenomena characterized by varying time-constants, is the extraordinary effect of very minute traces of nickel, referred to in our paper. The effect on phosphorescence produced by very minute traces of nickel is at least 10 times as great as that on fluorescence, and it is difficult to understand how a differential effect of this nature can be ascribed merely to a difference in the time-constant of the two phenomena.

Mr. Macnamara is quite right in his supposition that a brighter image would be obtained if the screen were operated at an angle and viewed from the front; employing a white reflector at the back of the glass surface. The practical realization of this arrangement is, however, one for the cathode-ray tube manufacturer and appears to us to be likely to present considerable difficulties. The question of whether a much brighter image would be obtained so that it could be projected is one demanding further study of the materials. It depends on the nature of the fluorescent preparation, because some varieties will stand considerably more bombardment without deterioration than others. On the other hand, it often happens that the materials which will stand electronic bombardment most satisfactorily are the most unsatisfactory ones from other points of view. We think it largely a matter for further research. Projection of the image is obviously very desirable, and if it were possible to obtain an illumination 10 to 20 times as great as we have at present, without destroying the fluorescent substance in a reasonable length of time, projection would be quite a possibility, and we should not like to rule it out as a possible future development.

With regard to the points raised by Prof. MacGregor-Morris, we do not believe that "burning" by cathode-ray bombardment, to which he refers, is a true temperature effect. The fluorescent materials of the type used are exposed to extremely high temperatures in the course of preparation and, up to a point, the higher the temperature the more intense is the fluorescence exhibited. The burning to which Prof. MacGregor-Morris refers is rather a destruction of active centres by electronic bombardment in the molecules and is not primarily a thermal effect. For this reason we do not believe that the backing of the fluorescent screens by a good thermal conductor would effect any improvement in this direction.

As explained in the paper, only the raster method

was employed in the measurements. Some sign of spot saturation was present, so that we can answer definitely that impulsive stimulation is less efficient than an equivalent uniform stimulation of the same mean intensity.

We have not yet carried out any experiments on the rate of growth and decay of the fluorescence under cathode-ray bombardment.

We are certainly not aware of the effect, mentioned by Mr. Jesty, of change of illumination with scanning speed; we doubt very much whether there would be any appreciable change with the materials considered in the paper. We have not found that the screen variations are as great as Mr. Jesty suggests are likely. Generally speaking, different tubes containing screens of the same fluorescent material give results within 10–15 per cent of each other.

We are very familiar with the phenomenon mentioned by Dr. Black, which we have called " negative ion burn." Our interpretation of the implied " mass spectrogram " does not agree with that of Dr. Black, as we have found the elements to be certainly lighter than oxygen; we ourselves diagnose them as a mixture of atomic and molecular hydrogen.

Coming to the points raised by Mr. Benham, we have not observed voltage saturation of the screen, but this is quite possibly due to the fact that the highest voltage employed by us in our experiments is 3 100 volts. Doubtless saturation would be experienced at greater voltages. As we have stated, the current saturation varies with the material in a very obscure way. Two preparations of the same material may be made and it will be found that one will saturate far more readily than the other. This is undoubtedly a subject which requires considerably more investigation.

The size of the raster used in our experiments was 65 mm square. The heat treatment that can be given depends upon the substance; zinc sulphide does not undergo any deterioration up to 400° C. It also depends upon the binder. If the binder is in excess, a certain amount of reaction with the zinc sulphide occurs. This spoils its fluorescence. Willemite is more robust than zinc sulphide in this respect. The tubes can, however, be heated up, with any of these substances, to the full amount required in the exhaustion, without injury. The difference in fluorescence response under cathode rays and ultra-violet light respectively is rather curious; we usually find that there is a small difference in shade —the colours are not quite the same. Whether this is due to the fact that the light from the ultra-violet lamp is not really only ultra-violet but contains a little violet and a little deep red as well, and that this affects the colour, we are not prepared to say, because we have not made the necessary experiments. Our experience is that certain shades, and notably the red ones, do look somewhat lighter under cathode radiation than under ultra-violet, and it is certainly not possible to judge the whites accurately. Z 23, which is white under the cathode ray, does not look white under ultra-violet.

Turning to the point raised by Mr. Scott regarding the effect of temperature on the light output of the fluorescence; this may be quite important. If similar substances are used for X-ray screens, and the screen is first examined at, say, 0° C. and is then examined at ordinary room temperature, say 20° C., it will be found that there is a very definite improvement in the luminosity at the higher temperature. We do not know at what temperature the improvement would cease, and we do not know whether the same effect is produced in the cathode-ray tube, but we suspect that it would be. It will be noticed that it is in the right direction, because warming up, to a point at all events, increases the luminosity. The effect of heat treatment during the exhaustion process will vary a great deal with different binders. Organic binders cannot be employed with any of the zinc sulphides, although they can be with the zinc silicates. The best thing to do would be to devise a method of entirely dispensing with binders, and we believe that this can be done. The binder introduces a disturbing factor, and the fewer the disturbing factors the better.

This also answers another question which was raised, as to the effect of the binder on saturation. It is possible that it does have an effect on saturation, because there is often some combination between the binder and the fluorescent substance, and this is why it is suggested in the paper that the amount of binder employed should be reduced to an absolute minimum, so that the fluorescent particles are simply anchored in position by attachment at one spot of their surface, and the majority of the fluorescent substance itself is free from the binder.

We cannot agree with Mr. Wilson's remarks regarding the de-activating action of very minute traces of nickel upon the phosphorescence, which he appears to have confused with that of " poisons." It is well known that many substances, such as iron, cobalt, chromium, and certain other heavy metals, if present in quite small quantities have a most detrimental effect on both the fluorescence and the phosphorescence exhibited. Nickel, if present in quantities of more than 1 part in 500 000, is also detrimental to both fluorescence and phosphorescence. The point is that we have found that the presence of quantities of nickel of 1 part in 1 000 000 or less are practically without effect upon the intensity of the fluorescence, which is wanted, but very largely destroy phosphorescence, which is not required. It is this *differential* effect of the presence of a trace of nickel, far more minute in relationship to its effect upon luminescent properties than has previously been considered, which has enabled us to produce non-phosphorescent—but highly fluorescent—zinc-sulphide and zinc-cadmium-sulphide preparations. These types of fluorescent bodies can thus be employed practically in many cases in which formerly they were useless owing to their intense phosphorescence.

The use of infra-red radiation as a de-activator has been known for a long time, but it is quite different from the use of nickel, because with nickel the phosphorescence which is not required is not excited at all—it no longer exists. In the case of exposure to infra-red, the phosphorescence exists and is destroyed by an outside source of radiation. The *modus operandi* is difficult to explain, but the quenching effect is easily affected by the exact method of manufacture.

The failure of the curves to pass through the origin can only be ascribed to errors of measurement. It

will be noted that in the more accurate photoelectric measurements the curves do in fact pass through the origin.

With regard to Mr. Samphier's communication, during the measurements the spot was kept in focus to the best of our ability. We have not made any measurements of the actinic value of the light emitted by materials specially prepared for photographic work. Such comparisons have been made in the case of intensifying screens used for X-ray purposes, and experience in this direction shows that zinc-sulphide preparation G 86 is several times as effective as calcium tungstate, the exact ratio depending upon the voltage employed. The duration of afterglow of various preparations can be controlled fairly closely. It is largely a question of the type of phosphorogen employed and the method of heating.

We are very grateful to Mr. Whipple for his most interesting communication and suggestions, and we shall certainly endeavour to carry out the investigation he suggests in the future. We have no comment to make, except that his results appear to confirm very clearly the presence of response components with varying time-constants.

Mr. L. S. Piggott (*in reply*): Several speakers have raised the question of how the gas-focused oscillograph recovers its good focusing properties when the frequency is raised sufficiently high. The most probable explanation seems to be that given by Hollmann, for a repeated trace (such as the ellipses shown in the paper). The positive ionization at any point in the path of the beam has insufficient time to disperse before the beam once more passes the point. Thus we have a "sheet" of ionized gas generated by the beam and extending from the deflecting plates to the fluorescent screen. In the case of the elliptic traces, this sheet is a conical surface. The effect on the beam is to give a "spot" which is sharply focused across, but not along, the trace. As the frequency is raised still higher, the focusing should improve, as the time between successive passages of the beam past any point (and therefore the de-ionization time) is reduced.

It is in view of the above theory that I feel justified in discussing the focusing of gas-focused tubes at very high frequencies in terms of frequency and not, as Mr. Puckle would, in terms of writing-speed. However, at radio frequencies the correct way to consider focusing phenomena is in terms of writing-speed. An attempt was made to keep the length of the traces in Figs. 2 and 3 constant, so that the writing-speed at the centre of each trace was proportional to the frequency, since a sinusoidal deflecting potential was used at all frequencies.

Mr. Puckle's more elaborate method of correcting defocusing of the electron-lens tube with asymmetrical deflection is interesting, and is likely to give better results than that suggested in the paper.

In reply to Mr. Watson Watt, the sensitivity and phase effects were first demonstrated by Hollmann, but the complete theory of them was given by Mr. R. Mines in an appendix to a paper by Prof. J. T. MacGregor-Morris and himself* published prior to the paper by Messrs. R. A. Watson Watt and J. F. Herd. The initial credit is therefore due to Mr. Mines.

I agree with Mr. Puckle that for use at ultra-high frequencies a tube with deflection plate connections brought out at the sides would be a great advantage. In the arrangements used in my experiments there was undoubtedly considerable reflection at the base of the tube, where two feeders of different characteristics joined.

Prof. MacGregor-Morris's suggestion of a split-plate construction is interesting, and, if manufacturing and constructional difficulties could be overcome, it might be useful in a tube used for monitoring purposes.

* *Journal I.E.E.*, 1925, vol. 63, p. 1056.

LOSS OF REVENUE ON HEATING AND LIGHTING LOADS, DUE TO POOR VOLTAGE REGULATION

By F. S. NAYLOR, Associate Member.

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SUMMARY

Discussion on the subject of revenue loss due to poor voltage regulation has generally been of an inconclusive nature by reason of the fact that a quantitative basis has been lacking. After making an examination of the characteristics of low-tension electricity supplies to domestic lighting and heating consumers the author puts forward a method of calculating the amount of the loss, considering only cases where the principle of revenue loss can be reasonably said to apply. The results indicate that the loss is sufficiently large to warrant closer consideration than it has hitherto been given, and in certain cases to justify expenditure on network modification, or the installation of automatic voltage-regulator equipment to prevent voltage variation.

In order to show its relative importance the principle is applied to the calculations normally carried out when transformers are being purchased, and in the case considered it is shown that it completely outweighs in importance the cost of iron and copper losses.

INTRODUCTION

Supply engineers throughout the country are facing continuously the problem of maintaining the low-tension voltage to consumers within the limits laid down in the regulations of the Electricity Commissioners. These limits, originally set forth in El.C.38, were $\pm$ 4 per cent, and in special cases on incomplete rural distribution networks these limits were extended to + 4 per cent and − 8 per cent; the new Regulations set these limits at $\pm$ 6 per cent.

As long as the voltage is maintained more or less within these limits, the supply engineer and the consumers are content. Even when the voltage variations are far greater than those prescribed, very little is said and less is done. It is not the fault of the engineer, for the problem is not a physical but an economic one.

Particularly does this remark apply to rural areas where, over a given period of development, the ratio Revenue/(Capital expenditure) is small; and in deciding whether the expenditure involved in correcting voltage variation can be warranted it would appear that the question of loss of revenue from consumers, due to low voltage, is not receiving full consideration. Where voltage regulation is poor throughout a system the general procedure is to consider extensive modifications to the network. In particular cases of outlying low-tension distributors, however, the normal method is to consider the installation of automatic voltage-regulator gear at or near the low-tension supply points to the distributors.

It is the latter aspect only which is considered in this paper, and the object throughout is an endeavour to arrive at the gain in revenue by the installation of such gear at these points. The underlying principles of the methods described could be applied to the former general problem (network modification), but it has been purposely avoided for the sake of simplicity.

Briefly, the argument relating to loss of revenue due to poor regulation is typified by such a case as the following. Let it be supposed that we are supplying to a consumer a lighting or heating load and that the voltage of the supply falls by 10 volts, owing to regulation on the feeders, transformer, etc.; then on a 230-volt supply (which at no-load during the night we will assume reaches a maximum of 4 per cent above the declared voltage, i.e. 239·2 volts) the current will be 229·2/239·2 of the value it would have had if the voltage had remained constant. The voltage likewise having fallen to 229·2/239·2 of its original value, the consumption of electricity will be (229·2/239·2) × (229·2/239·2) = 0·918 of the amount it would have been on a constant 239·2-volt supply. The amount of revenue obtained from the consumer will be correspondingly less than if we had maintained the voltage at 239·2 volts. There is a real objection to an argument on these lines, for it does not take into account the manner in which voltage-drop takes place in practice, but it serves for the moment to illustrate the principle involved.

It has been necessary at the outset in preparing this paper to accept the principle of revenue loss. Whether this principle is true or not only a considerable amount of experience will show, but it is clear that, unless an examination of its application to actual network conditions be made and a theory be suggested to show a method of calculating the amount of the loss, this important factor will continue to be ignored. It is hoped that the following analysis will be useful as a guide to assist in watching this question, and in bringing it into its proper relation with the other problems to be considered in the distribution of electricity.

GENERAL CONSIDERATIONS

Practically all kinds of domestic lighting and heating appliances are affected by voltage-drop; in this connection reference should be made to Fig. 1, which shows the relation between the percentage reduction in energy consumption and the voltage-drop. The reduction (or increase) in consumption for such voltage variations as are normally encountered is 0·79 on purely lighting, 0·975 on purely heating, and, say, 0·9 on mixed lighting and heating, of that obtained on a resistance load unaffected by temperature. Thermostatically-controlled appliances will not be affected by voltage variation, but will operate for longer hours. Such appliances are not considered in this paper.

The manner in which revenue is affected by reason of the reduced consumption is largely governed by the

tariff under which energy is being sold. A high rate per unit will mean a greater loss than a fixed charge, independent of maximum demand, and a low unit running charge. Furthermore, there are a number of other aspects which must not be left out of account. In the first place, in the event of excessive voltage-drop taking place, a consumer might replace a lamp by one of higher power rating; secondly, for the same reason, he might switch on two fire bars instead of one. With small voltage-drops, however, a consumer would not be sufficiently concerned to carry out either of these actions. Thirdly, as regards cookers, with an excessive voltage-

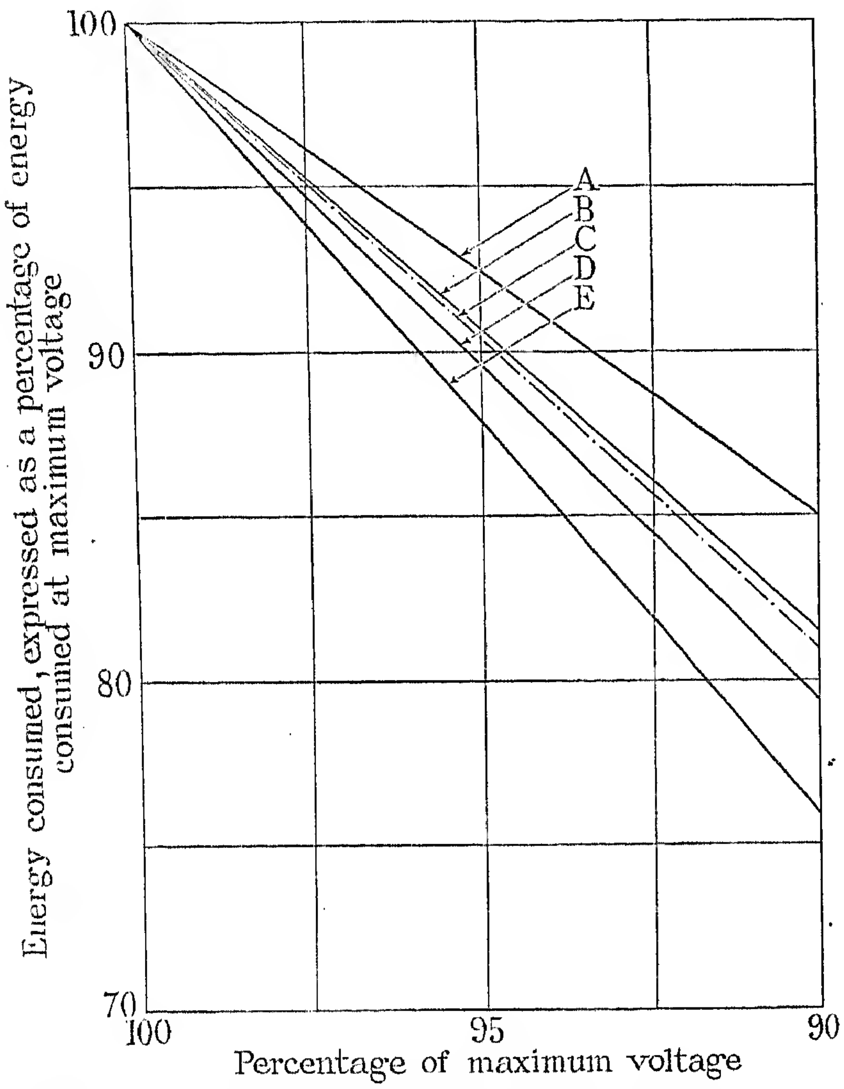

Fig. 1.—Curves showing reduction in consumption due to voltage-drop.

The following figures show the reduction in energy consumed compared with a resistance unaffected by temperature (taken as unity):
A. Lighting (60-watt gasfilled lamp) = 0·79.
B. Fire = 0·975.
C. Resistance unaffected by temperature = 1·0.
D. Wireless set (average for curve) = 1·1.
E. Lighting (400-watt gaseous discharge lamp) = 1·26.

drop the cooker might be discarded altogether, whereas with only slight voltage reduction it might be used for slightly longer periods for the same cooking operation with increased consumption, or with transformer-operated boiling plates with decreased consumption.* Fourthly, if after a considerable period the consumer set a limit on the amount he was prepared to pay per quarter for his electricity, and voltage-drop was suddenly corrected and maintained at its correct value, then he might set out to economize in the use of his domestic appliances.

* F. S. Naylor and C. Bacon: *Electrical Review*, 1935, vol. 116, p. 268.

It would appear, therefore, from a consideration of the above points, that for large variations of voltage all types of apparatus can be affected from a revenue-earning point of view; but with small variations, only lighting, fire, and wireless-set loads can with certainty be said to be affected in a manner which lends itself to calculation. The author has considered only low-tension distribution loads comprising lighting and heating of the latter type, and has formed estimates of revenue loss where the voltage-regulation values at the points considered are relatively small, i.e. of the order of $\pm$ 4 per cent of the declared voltage. Actually, a range of + 4 per cent and − 8 per cent of the declared voltage has been taken for comparative purposes.

CORRELATION OF REGULATION AND LOAD ON LOW-TENSION DISTRIBUTORS

Definition of "Effective Network Impedance"

In arriving at estimates of revenue loss due to regulation at a point (generally the supply point) on a low-tension distributor, it has been essential to show the relationship which exists between the voltage regulation and the load, and in doing this it has been necessary to introduce the term "effective network impedance." Briefly, the factors which produce the regulation at the point are primarily impedance-drops in high-tension feeders and transformers between the main source of supply and the point. They are produced not only by the load under consideration but possibly by a whole variety of loads fed off at intermediate points before the particular low-tension distributor point is reached. Secondary factors are network layout and the types of bulk supply drawn therefrom, both of which may necessitate a control of the high-tension voltage at the main source of supply ill-suited to the particular point being dealt with. All these factors can be lumped together and be assumed to be represented by a variable impedance R, which is referred to as the equivalent or effective network impedance at the point considered, and is equal at any instant to the voltage-drop divided by the load current. The loss of revenue due to energy not supplied will be some definite function of the voltage regulation, or, to put it in another way, of R.

The following cases have been selected—out of a mass of data relating to conditions in the Midlands and collected by the author over a period of 2 years—to show how R can be evaluated, and how a basis for calculation can be arrived at.

Fig. 2 shows voltage-drop and load-current records at the outgoing supply point to a group of low-tension distributors supplying lighting and heating loads only, to a residential area. The supply is given by means of a high-tension overhead line to a kiosk substation containing a 250-kVA transformer, the outgoing low-tension distribution being 3-phase, 4-wire, 230 volts, 50 cycles per sec. The records shown are for three consecutive Thursdays, on the last of which the peak load occurred for the year. By dividing the voltage-drop by the load current at every instant, further curves of effective network impedance in ohms have been plotted. These additional curves form an interesting study in themselves, but the clear fact emerges that in relation to the load

current the effective network impedance is generally lowest at the period of maximum demand, and in this case amounts to 0·0384 ohm when the load is 340 amps. The author suggests that the reason lies in the fact that when the load is at its maximum (i.e. 340 amps.) it bears its greatest ratio to all other loads entering into the production of the voltage-drop than at any other time; and consequently, the voltage-drop per ampere of load current, i.e. the effective network impedance, represent the everyday loadings with a fairly close degree of accuracy. There are a considerable number of other supplies given in a like manner from the generating station, but these are not shown. For the greater part of the time it is not possible to make any material correction on the regulation at the point considered, because of the necessity of keeping constant the voltage of the supply to large industrial consumers and because the considerable ramifications of the various portions of

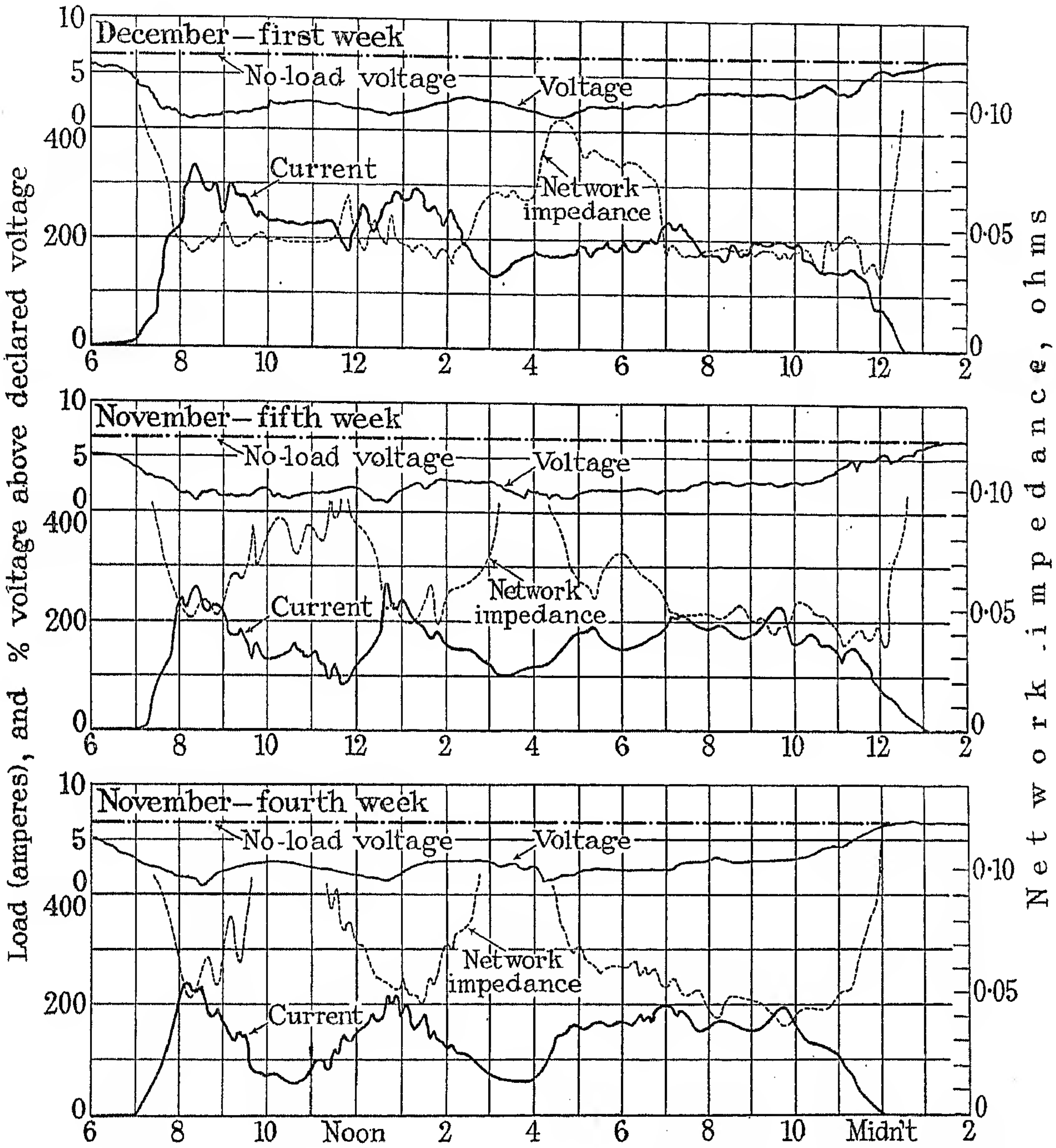

Fig. 2.—Daily load curves of supply from transforming substation in residential area, on 3-phase 4-wire 230-volt supply.

is lowest at that period. The minimum value will be referred to as R_1.

In order to explain the point more fully the author has prepared the following analysis of a section of a system (see Fig. 3) in a fairly large town in the Midlands, and has shown (see Fig. 4) the loadings throughout the section for various values of total distributor load on substation No. 7. The percentage regulation throughout the section is tabulated in Table 1. The effective network impedance is derived in Table 2, and it will be observed that it tends to be lowest at the maximum-load period on the distributor. The data for this analysis were taken from readings observed over a considerable period, and they the network—giving supplies of widely differing characteristics—make it impossible to control the voltage merely for this one individual distributor. The tappings on the transformer in No. 7 substation are set so that during a normal afternoon when there is no load on the transformer the voltage is 4 per cent in excess of the declared value, the high-tension voltage correction having been taken from the high-tension control chart at the generating station.

Application of Effective Network Impedance R_1

The effect of assuming the effective network impedance to remain at the minimum value R_1 throughout the year

Table 1

VOLTAGE REGULATION AT SUPPLY END OF L.T. DISTRIBUTOR FED FROM SUBSTATION NO. 7 DUE TO NETWORK IMPEDANCE, WITH DUE ALLOWANCE FOR H.T. VOLTAGE CORRECTION

Load on l.t. distributor	Full load early evening mid-winter	0·75 load Feb. and Oct. (average)	0·6 load winter peak	0·25 load late evening summer	No load afternoon summer	No load after midnight autumn
Diagram reference (Fig. 4)	A	B	C	D	E	F
Percentage regulation at :—						
Main trunk feeders	0·781	0·560	1·008	0·267	0·567	0·229
1st to 2nd substation	0·205	0·135	0·230	0·091	0·112	0·068
2nd to 3rd substation	0·214	0·138	0·238	0·097	0·106	0·059
3rd to 4th substation	0·364	0·244	0·397	0·160	0·143	0·076
4th to 5th substation	1·120	0·803	0·916	0·410	0·176	0·112
5th to 6th substation	1·322	0·970	0·853	0·382	0·129	0·029
6th-substation transformer	1·560	1·170	0·936	0·390	0	0
6th to 7th substation	3·515	2·636	2·110	0·878	0	0
7th-substation transformer	3·250	2·439	1·950	0·813	0	0
Total percentage regulation due to network impedance	− 12·331	− 9·095	− 8·638	− 3·488	− 1·233	− 0·573
Correction due to h.t. control	0·000	− 1·118	+ 1·233	− 1·902	+ 1·233	− 2·685
Total percentage variation at supply end of l.t. distributor (i.e. l.t. terminals of 30-kVA transformer in substation No. 7)	− 12·331	− 10·213	− 7·405	− 5·390	0	− 3·258

Table 2

EFFECTIVE NETWORK IMPEDANCE PRODUCING REGULATION AT SUPPLY END OF L.T. DISTRIBUTOR

Diagram reference (Fig. 4)	A	B	C	D	E	F
Total percentage variation at l.t. terminals of 30-kVA transformer substation (i.e. supply end of l.t. distributor) below maximum l.t. voltage	− 12·331	− 10·213	− 7·405	− 5·390	0	− 3·258
Total variation (in volts) below maximum voltage at no load (condition E); declared voltage 200 volts	24·662	20·426	14·810	10·780	0	− 6·516
Load current (in amps.) per phase on l.t. distributor	36	27	21·6	9	0	0
Effective network impedance (in ohms) with respect to load current on l.t. distributor	0·685	0·758	0·687	1·198	—	—

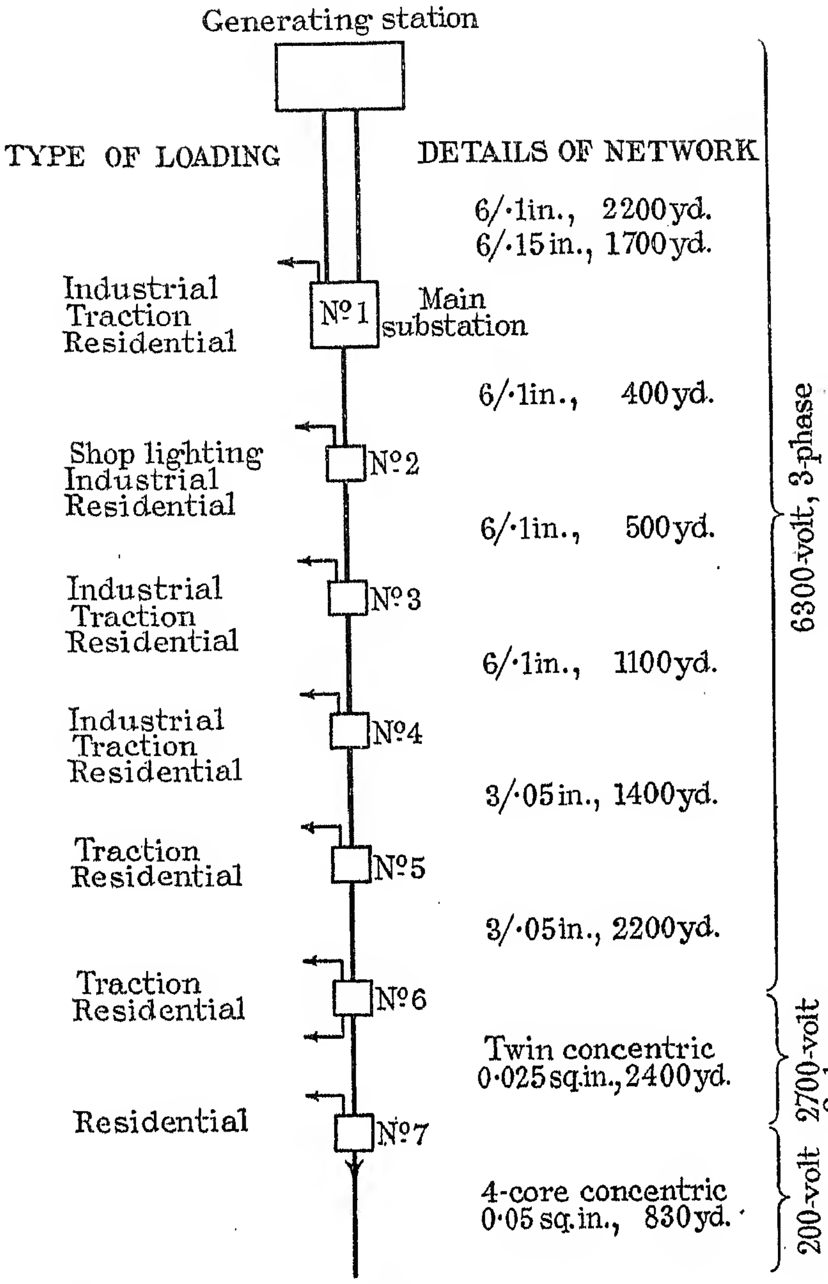

Fig. 3.—Typical high-tension network supplying low-tension distributor.

instead of only at the maximum distributor load period, is shown in Figs. 5, 6, and 7. These are three separate cases of distributor load/voltage records taken at the outgoing low-tension supply points. In each case R_1 is calculated, and additional voltage curves are plotted on the above assumption. In practically all cases the assumed voltage curve is not so bad as the actual voltage chart. Clearly, the calculated loss due to the assumed drop will not be so great as that due to the actual drop. The former, however, is used to ensure that, when the matter is regarded from the other point of view, namely, the gain of revenue by voltage improvement, the results will preferably be low.

ALTERATION TO LOADING OF LOW-TENSION DISTRIBUTORS PRODUCED BY VARYING THE VOLTAGE AT THE SUPPLY END

Curve (*a*), Fig. 8B, represents the kilowatt load curve for a substation supplying low-tension distributors; the curve is drawn accentuated, for convenience. The voltage supplied is assumed to vary as shown in curve (*a*), Fig. 8A, fluctuating between 4 per cent in excess of declared voltage at no load and a value below declared voltage at full load on the transformer. In Fig. 8B, curves (*b*), (*c*), and (*d*) respectively indicate the loading which would have been obtained if the voltage at the low-tension terminals had been adjusted so as to (*b*) maintain constant declared voltage, (*c*) obtain a voltage fluctuation between 4 per cent in excess of declared voltage at no load and declared voltage at full load, (*d*) maintain a constant voltage of 4 per cent in excess of declared voltage.

It is clear from Fig. 8B that in all cases except (*b*) there will be an increase in the energy supplied; in case (*b*) it is difficult to say whether there is an increase or a decrease. Furthermore, it is clear that there is in all cases an increase in the maximum demand on the transformer substation.

In the Appendix, equations are given for calculating

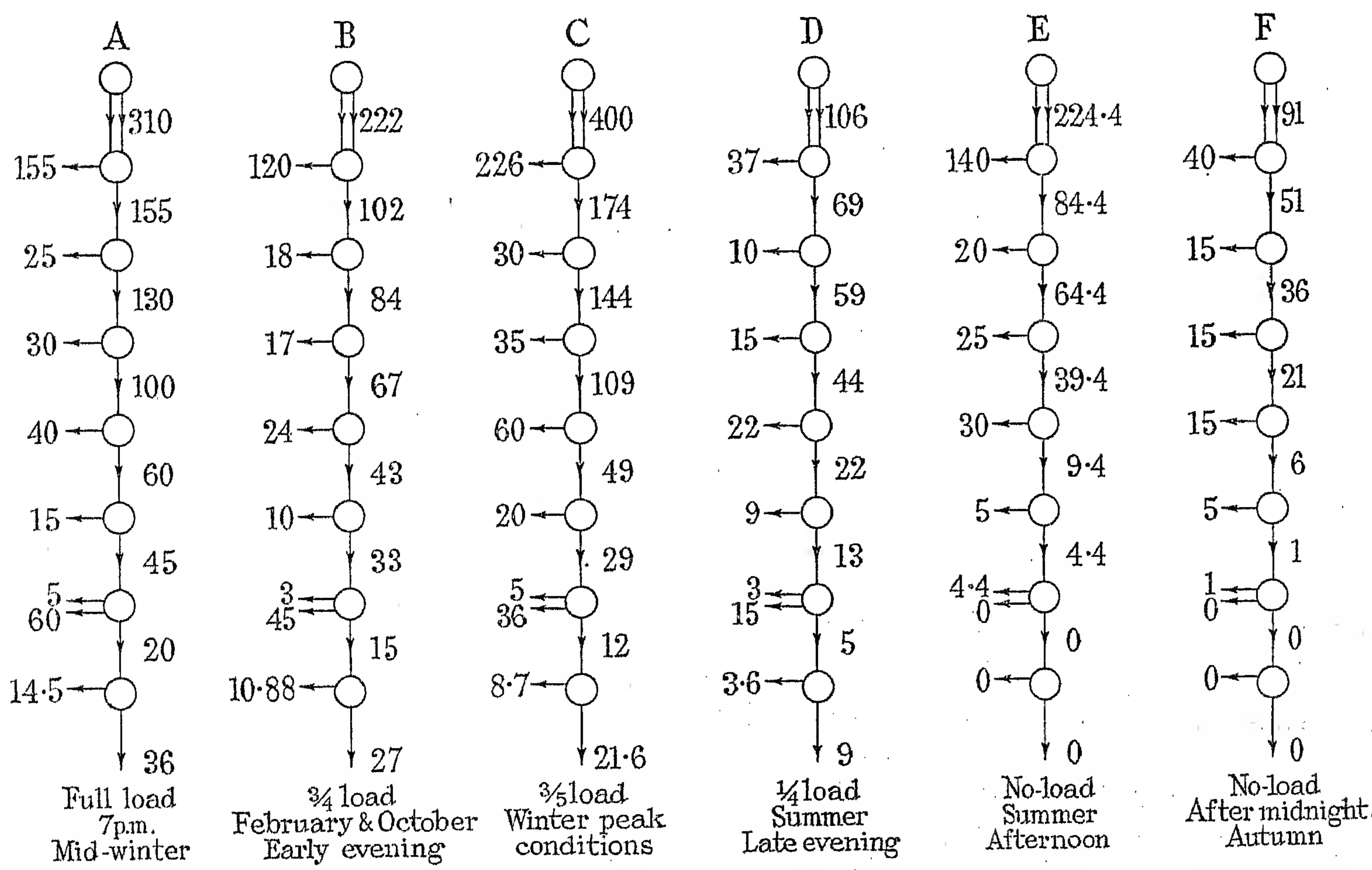

Fig. 4

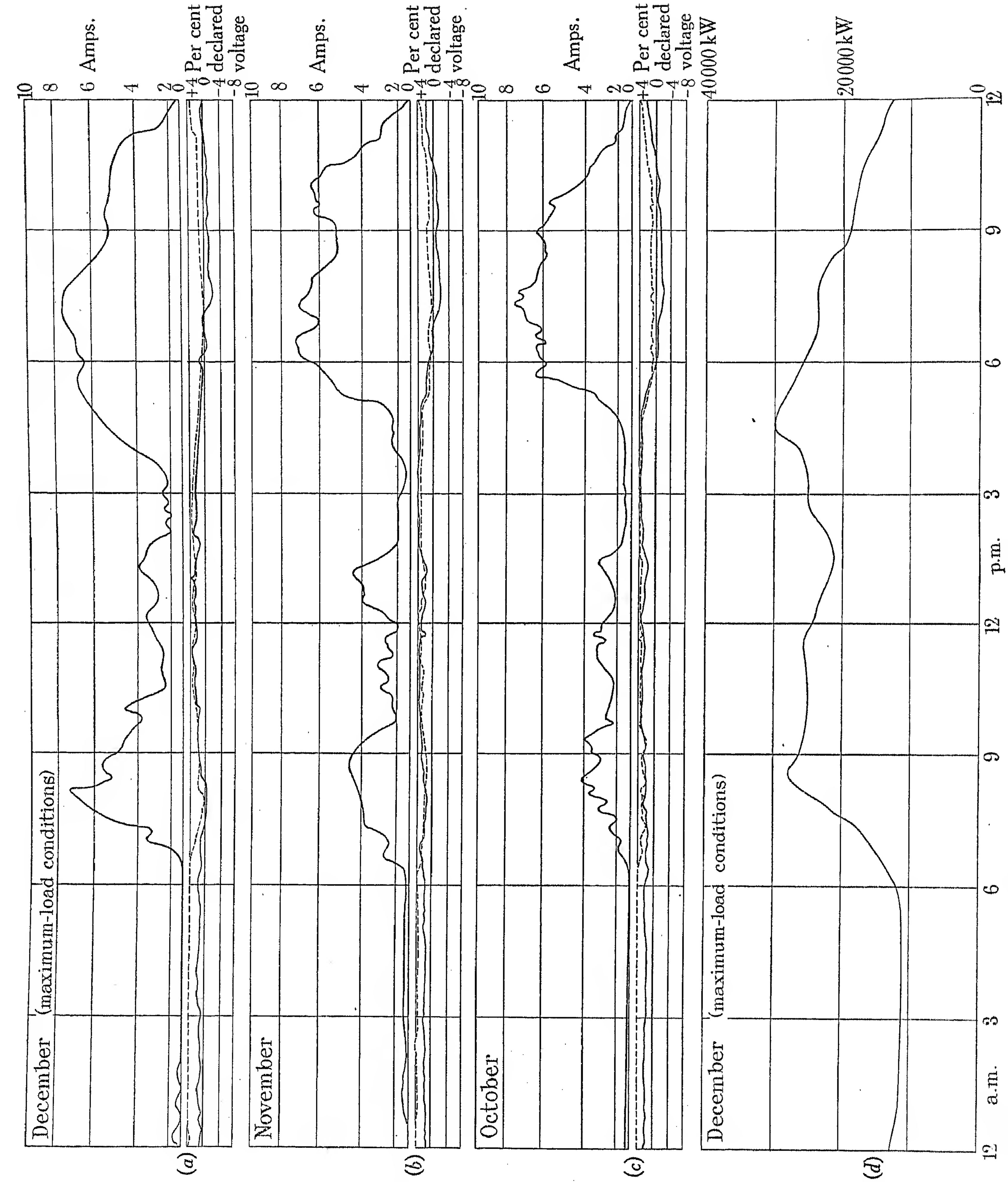

Fig. 5.—(a), (b), (c): Amps. loading (h.t.) and voltage variation at l.t. terminals of 100-kVA transformer. (d): Total loading of undertaking.

the effect on revenue of giving supplies for the transformer substation with voltages either as (a), (b), (c), or (d), but it is sufficient to state at this stage that the greatest improvement is obtained by maintaining at the substation terminals the maximum permissible voltage as given under (d), and all the curves and examples given throughout the paper are based on the assumption that this improvement is obtained.

Briefly, the improvement in revenue is the direct result of the increase in units supplied, against which must be offset in most cases the cost of the increased maximum demand on the system.

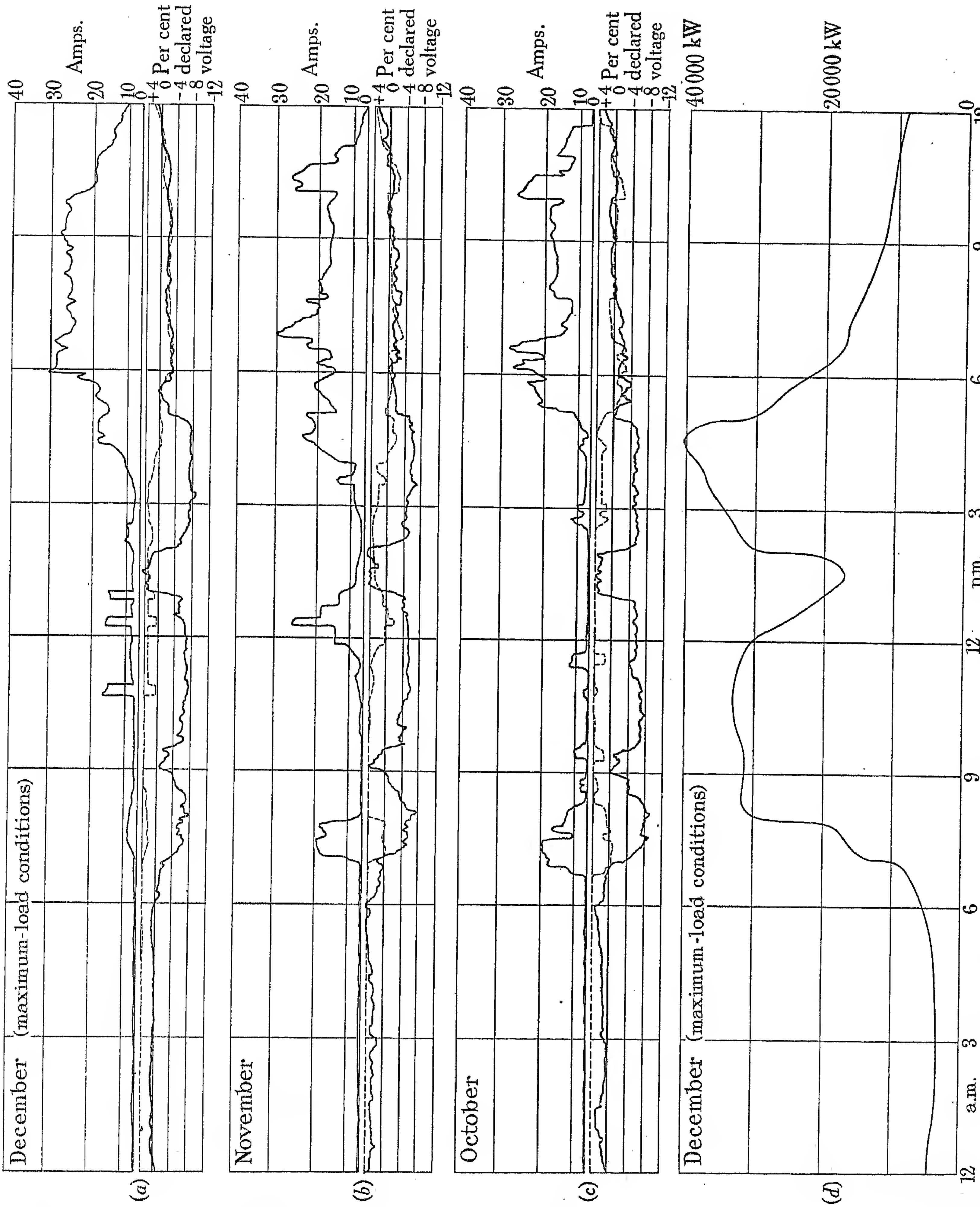

Fig. 6.—(*a*), (*b*), (*c*): Amps. loading and voltage variation at supply end of distributor. (*d*) Total loading of undertaking.

The increase in units will be proportional to both the load at the point of supply and also the magnitude of the voltage variation taking place before the improvement. Reed* has already evaluated the increase for a transformer alone in a case where the regulation is due to the equivalent resistance R of the transformer. In his case, with respect to the load on the transformer, R is a fixed quantity. In the present case, with respect to the load on the substation, the effective network impedance R is a variable quantity having in general

* E. G. Reed: "The Essentials of Transformer Practice" (D. Van Nostrand, New York).

Fig. 7.—(*a*), (*b*), (*c*): Amps. loading and voltage variation at supply end of distributor. (*d*) Total loading of undertaking.

its minimum value R_1 during the period of maximum demand. The author has arrived (see Appendix) by a different method at the same result as that due to Reed, but employing the minimum effective network impedance (R_1) to ensure that his estimates of increased output will preferably be understated. Fig. 9 gives the increased output on mixed lighting and heating loads over that obtained for various conditions of regulation, plotted to a base of load factor.

The increase in system maximum demand as a result of the increase of maximum demand on any individual distribution substation is indicated by the investigations of

Woodward and Carne.* For the types of loads coming within the scope of this paper, a comparison of the effective demands of the same loads on the low-tension and high-tension networks respectively shows that diversity factors up to 2·0 are normal. The author's own investigations (Figs. 5, 6, and 7) also indicate that the loads on the substations or distributors considered are 0·75, 0·625, 0·285 respectively of the substations' maximum demand at the time of the system maximum demand, corresponding to diversity factors of 1·33, 1·6, and 3·5 respectively, taking the whole of the system substations into account. In the Appendix a simple relation is given between system maximum demand and the average load on low-tension distributors at the time of occurrence of the former, in terms of the diversity. Using this relation, Fig. 10 gives the increase in the bulk-supply maximum demands on mixed lighting and heating loads over that obtained for various conditions of voltage regulation, plotted to a base of diversity factor.

The following cases show how the curves can be used for estimating revenue loss, stress being laid on the

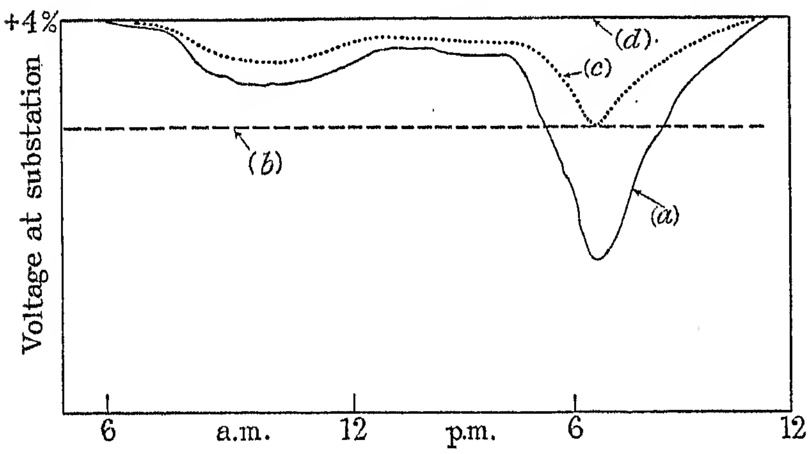

Fig. 8A.—Voltage records obtained at substation.

(a) Voltage actually obtained.
(b) Declared voltage.
(c) Voltage fluctuating between declared voltage and 4 per cent in excess of declared voltage.
(d) Voltage 4 per cent in excess of declared voltage.

magnitude of the possible annual gain as compared with the capital charges on the cost of voltage-correcting equipment if the latter be installed.

As a final example, the performances for a certain duty of two transformers of different inherent regulation are compared, introducing the factor of loss of revenue. While this has nothing to do with the main object in hand, it at least brings home the necessity of thrashing out the principle of revenue loss so that its acceptance or rejection can be properly decided and its correct position allocated as a factor in the design of electrical distribution schemes.

(i) Application to 60-kVA Rural Substation, Energy being sold at Various Tariffs

The case of a 60-kVA transformer substation supplying a large village will illustrate the application of the curves. It is found that the annual output from this substation is as follows: Lighting at 7·2d. per unit, 23 118 units; heating at 1·8d. per unit, 15 056 units; combined lighting and power at fixed charge plus 1d. per unit (cooking load negligible), 32 734 units; power (average price $1\frac{1}{2}$d. per unit), 7 646 units. Neglecting the power load, the total output from this transformer amounts to 70 908 units per annum, and with the transformer loaded to 50 kW at the substation peak the load factor of this supply amounts to 70 908/(50 × 8 760) = 16·2 per cent. The revenue is as follows:—

32 734 units at 1d. per unit (taking running charges only)	= 32 734d.
23 118 units at 7·2d. per unit	= 166 200d.
15 056 units at 1·8d. per unit	= 27 100d.
	226 034d.
	= £943

Energy is purchased at the main substation at £3 5s. per kW of maximum demand plus 0·185d. per unit.

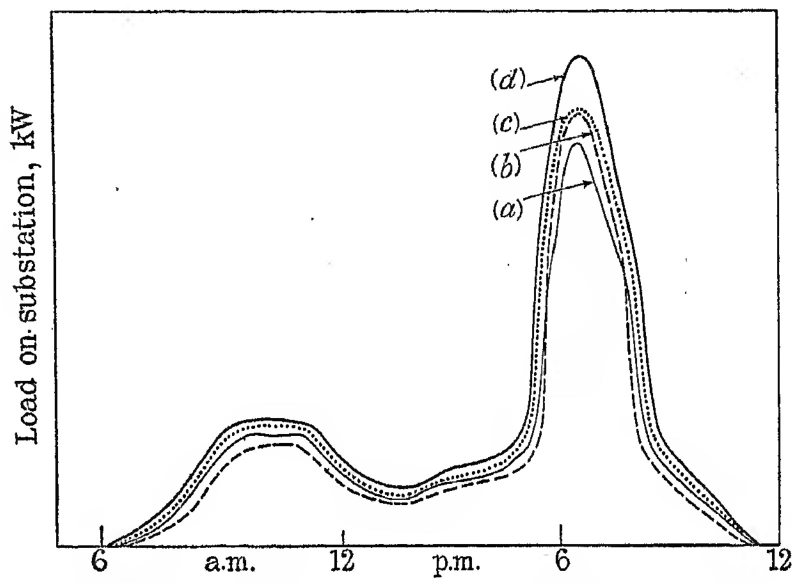

Fig. 8B.—Kilowatt loads obtained at substation.

(a) At actual voltage, with positive and negative fluctuations.
(b) At declared voltage.
(c) At voltage fluctuating between declared voltage and 4 per cent in excess of declared voltage.
(d) At voltage 4 per cent in excess of declared voltage.

Additional items to cover e.h.t. and h.t. transmission, substations, losses, management, etc., must be added to obtain the cost of supply at the h.t. terminals of the substation. The cost of these items is, however, independent or almost independent of load and arises from voltage-drop considerations. Any small increment of load which can be placed on the substation without aggravating the voltage regulation to low-tension consumers can be charged at the net bulk-supply costs. The bulk-supply cost of the units amounts to 70 908 × 0·185d. = £55 per annum. The difference between the income from, and the cost of, the units amounts to £943 − £55 = £888 per annum. It was found in this particular case that the voltage variation on the low-tension side was ± 4 per cent at full load, i.e. during the lighting-peak period in winter.

Referring to curve (b), Fig. 9, it will be observed that at a load factor of 16·2 per cent, the percentage increase of units which can be supplied by giving energy at 4 per cent above the declared voltage at the transformer terminals, instead of allowing a variation of ± 4 per cent, amounts to 8·6 per cent. Applying this figure to the

* *Journal I.E.E.*, 1932, vol. 71, p. 852.

example under consideration, the increased profit from units alone amounts to 8·6 per cent of £888 = £76 per annum.

The maximum demand on the system is brought about by small factories in the area between the hours of 4 p.m. and 4.30 p.m., and the maximum demand on the transformer under consideration occurs at about 7 p.m. Records show that the transformer is at approximately 0·55 full load during the system maximum-demand period, corresponding to a diversity of 1·8.

It will be observed from curve (*b*), Fig. 10, that the increase in the bulk-supply maximum demand, with a diversity (m) of 1·8, will be 5 per cent of 50 kVA, i.e. 2·5 kVA, giving an increase in the supply cost of 2·5 kVA at £3·25 per kVA, namely £8. The net profit derived from supplying at 4 per cent above the declared voltage therefore amounts to £76 − £8 = £68. In consequence of the network arrangements and the limitations set by various bulk supplies, it is quite impossible in this case to correct the variation in low-tension voltage by varying the high-tension voltage. The cost of fitting automatic voltage-regulator equipment to a 60-kVA transformer might

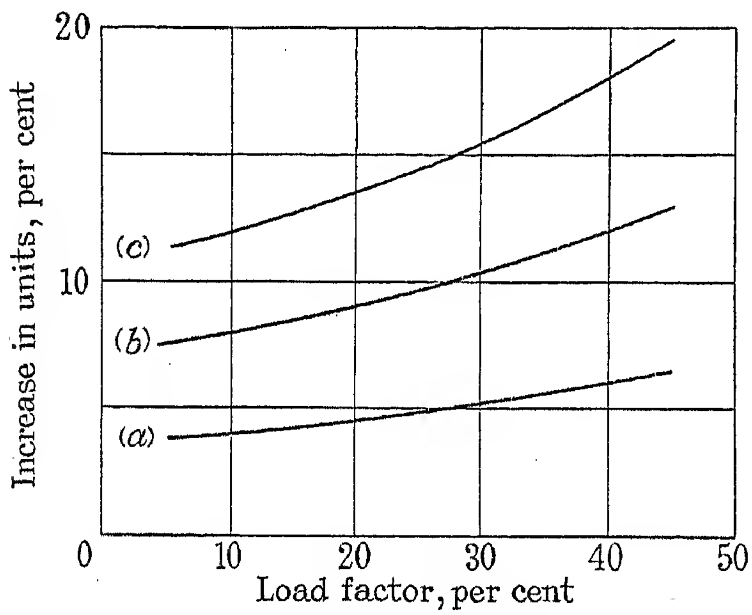

Fig. 9.—Curves showing increase in distributor load obtained by maintaining, at the supply end, the voltage at 4 per cent in excess of the declared voltage the whole of the time instead of allowing it to fall at full load to:—
(*a*) Declared voltage.
(*b*) 4 per cent below the declared value.
(*c*) 8 per cent below the declared value.

amount to £120. The capital charges at 10 per cent per annum would therefore not exceed £12 per annum. It is thus an economic proposition to install this type of gear in order to lift up the voltage as prescribed, the margin of profit being £68 − £12 = £56 per annum.

It may be noted in passing that the cost of regulator losses have been ignored, partly for the sake of simplicity, and partly because they are, generally speaking, of negligible importance.

(ii) Application to Individual Domestic Tariffs

The previous example leads to the consideration of the question whether a gain in revenue will always result from the prevention of low voltage, whatever the tariff under which energy is being sold.

A transformer substation having a 100-kVA capacity has therefore been considered, loaded in either of the following ways:—

(i) Lighting load only, with a load factor of 10 per cent, all energy being sold at 4·5d. per unit.

(ii) Domestic lighting and heating load, with a load factor of 25 per cent, all energy being sold at a fixed charge per consumer plus a running charge of 0·6d. per unit.

(iii) Domestic lighting and heating load, with a load factor of 25 per cent, all energy being sold at a fixed charge per consumer plus a running charge of 1d. per unit.

(iv) Domestic lighting and heating load, with a load factor of 15 per cent, all energy being sold at £10 per kW of maximum demand of the lighting supply only, plus a running charge of 0·6d. per unit.

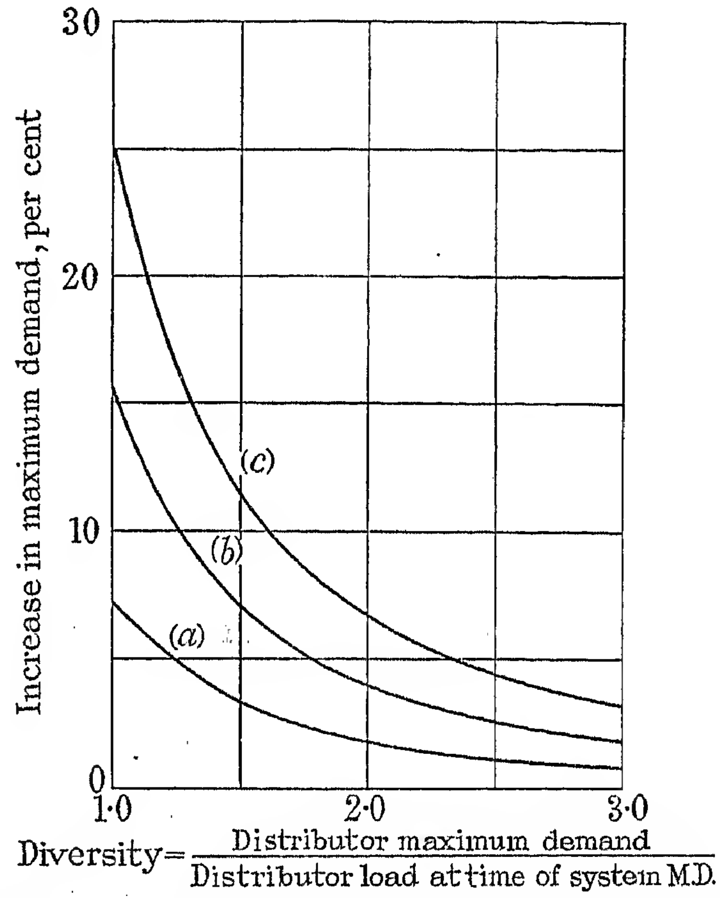

Fig. 10.—Curves showing increase in distributor maximum demand (affecting the system bulk-supply maximum demand) obtained by maintaining, at the supply end, the voltage at 4 per cent in excess of the declared voltage the whole of the time instead of allowing it to fall at full load to:—
(*a*) Declared voltage.
(*b*) 4 per cent below the declared value.
(*c*) 8 per cent below the declared value.

The transformer, in conjunction with numerous others, takes its supply in bulk at £3 5s. per kW of maximum demand and 0·2d. per unit. Various diversity factors are assumed on the maximum demands under the various tariffs. The increase in revenue derived by maintaining the output voltage to the low-tension distributors at 4 per cent in excess of declared voltage, instead of various conditions of normally-occurring regulation, is given in Table 3.

In practice, energy would be sold under more than one tariff, and a normal case, for example, would lie between (i) and (ii) or between (i) and (iii).

The following conclusions can be drawn from Table 3:

(*a*) There is a very appreciable increase in revenue on

lighting loads, where the flat rate per unit is of necessity always high.

(*b*) Revenue is affected to the greatest degree where energy is being sold on a 2-part tariff with a maximum-demand charge. The increase in revenue is large for comparatively small increases in the average voltage.

(*c*) Revenue is least affected where energy is being sold on a 2-part tariff with a fixed charge dependent on floor area, rateable value, etc., and not directly dependent on the maximum demand.

(*d*) The increase of revenue in many cases is of a magnitude sufficient, apart from other considerations, to warrant the installation of the automatic voltage-regulation gear upon economic grounds.

(*e*) Bearing in mind that the table shows the increase for 100-kVA loads, there would appear to be economic grounds under certain conditions for installing automatic voltage gear on low-tension distributor loads as small as 25 kVA.

In connection with item (*c*), a sliding-scale tariff equivalent to the type of tariff considered would give a considerably greater revenue increase, and from this point of view the former would be a preferable tariff.

(*b*) The units sold for lighting and heating being known from the total of the consumers' accounts, the load factor can be calculated.

(*c*) The percentage increase obtained in units sold and in the bulk-supply maximum demand by maintaining the voltage constant at 4 per cent in excess of the declared value, can be determined by referring to Figs. 9 and 10.

(*d*) From the percentage increases given in Figs. 9 and 10, the effect on revenue can be determined in a similar manner to that employed in the example of a 60-kVA rural substation (see page 41).

(*e*) The annual increase in revenue can be compared with the capital charges per annum incurred in correcting the voltage fluctuations, and the economy of so doing ascertained.

(iv) Application to the Purchase of Distribution Transformers Supplying Residential Areas

From the foregoing, it would appear desirable to incorporate the principle of revenue loss in the calculations usually employed when transformers are being purchased for low-tension distribution purposes.

Table 3

Cost of bulk supply	£3 5s. per kW of maximum demand + 0·2d. per unit			
Type of load	Lighting only	Domestic lighting and heating		
Load factor, per cent	10	25	25	15
Diversity factor	1·0–2·0	1·6	1·6	1·75
Price of electricity to consumers	4½d.	1d.	0·6d.	£10 per kW + 0·6d.
		(Running charge only taken into account)		
Voltage regulation occurring at substation maximum-demand period	Increase in revenue, £ per annum per 100 kW maximum demand of l.t. distributor load, due to maintaining voltage at substation at 4 per cent above declared value			
+ 4 per cent and 0	39–57	25	8	74
± 4 per cent	75–112	50	14	157
+ 4 per cent and − 8 per cent	107–166	72	20	249

(iii) Suggested Application of these Principles in Practice

Where supplies are being given, the revenue from which is affected by voltage-drop, and where fluctuations exist which cannot be corrected by variations in high-tension voltage, it is suggested that the following procedure be adopted:—

(*a*) Firstly, the actual limits should be ascertained under the maximum-demand periods. If any doubt occurs as to what values should be taken, the no-load voltage should be regarded as the maximum occurring during the daytime, while the full-load voltage should be taken as the maximum occurring when the transformer is taking its maximum load during the week when peak-load conditions are being obtained on the undertaking as a whole. In all cases, readings must be taken by means of recording instruments.

The general method adopted is to assume that a certain number of kilowatts of load is available, and on this assumption to compare the capital charges and the cost of iron and copper losses for various offers. In actual fact, the transformer to be purchased will be placed in a substation, upon which will be imposed, not specific kW loadings, but rather specific admittance loads.

With regard to the high-tension voltage, from the evidence so far obtained there seems to be no indication that this is varied to suit, or to overcome, the regulation of such transformers as the one being dealt with, so that the only reasonable method of comparison is to assume that the same voltage will be applied at the high-tension terminals whatever transformer is installed. The following formulæ can be used for calculating the various items under consideration:—

(1) Capital charges $= 0\cdot01p \times$ £

(2) Increase in bulk-supply costs due to iron loss
$$= 0\cdot0365Id + 0\cdot001Ik$$

(3) Increase in bulk-supply costs due to copper loss
$$= 0\cdot000365CFNd + 0\cdot001\frac{Ck}{m^2}$$

(4) Reduction in revenue due to regulation
$$= 0\cdot0065\theta WFN(D - d)$$
$$+ 0\cdot018\theta W\left(K - \frac{k}{m^2}\right)$$

where

p = Interest and sinking-fund charges on the capital to be expended;

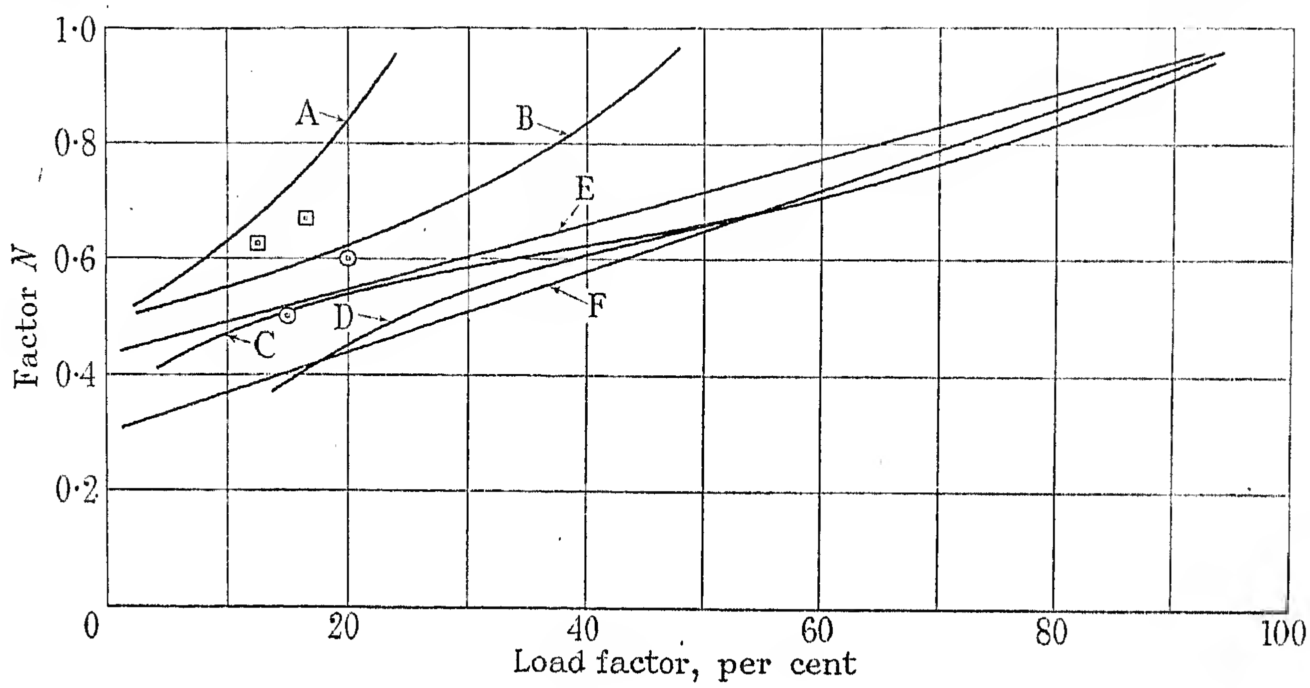

Fig. 11.—Values of the factor N for various types of load.

Curve A.—Pure lighting load assumed to exist for 25 per cent of the year; derived from $N = 0\cdot25/(0\cdot5 - F)$.
Curve B.—Lighting and heating load assumed to exist for 50 per cent of the year; derived from $N = 0\cdot50/(1\cdot0 - F)$.
Curves C and D.—Mixed lighting, heating, and power load, the latter predominating; derived from Dr. Ekström's equations:

$$N = \frac{1}{F}\left[a^2 + \frac{2a(1-a)}{\lambda+1} + \frac{(1-a)^2}{2\lambda+1}\right]$$

where a has the values 0·01 and 0·05 respectively.
Curve E.—Mixed system loads as for curves C and D, derived from form-factor curves given in British Insulated Cables Co.'s "Handbook" (p. 220), and *Electrician* (1932, vol. 109, p.450), where $N = K^2F$.
Curve F.—Mixed system loads as above, derived from D. J. Bolton's loss-factor curves given in *World Power* (1932, vol. 17, p. 14), where $N = 0\cdot3 + 0\cdot7F$.
⊙ Lighting and heating load, derived by W. Fennell and given in the Overhead Lines Association's Specification for Rural Transformers.
⊡ Lighting and heating load, derived by the author from load-curve data.

I = Iron loss (watts) in the transformer at normal voltage;

C = Copper loss (watts) in the transformer at full load;

F = Load factor on the transformer, expressed as a percentage;

N = Factor taken from Fig. 11, expressed as a decimal;

θ = Percentage regulation at unity power factor at full load on the transformer;

W = Full load (kW) or maximum demand on the transformer;

m = Diversity factor, expressed in the form greater than unity;

d = Pence per unit paid by the undertaking for the bulk supply;

k = £ per kW of maximum demand paid by the undertaking for the bulk supply;

D = Average price paid by the consumers per unit on the transformer in question; and

K = Price per kW of maximum demand paid by the consumers on the transformer in question.

Taking p as $8\frac{1}{2}$ per cent, and the cost of the bulk supply as £3 5s. per kW of maximum demand + 0·18d. per unit, the average price paid by the consumers is 3d. per unit, made up of 60 per cent lighting at $4\frac{1}{2}$d. per unit and 40 per cent radiators at $\frac{3}{4}$d. per unit, a load factor of 15 per cent, $N = 0\cdot58$, and a diversity factor of 1·5.

Table 4 shows the annual running costs for each of the above four items, and in total, for two offers for the supply of a 25-kVA transformer. The first transformer is priced at £44, with an iron loss of 168 watts, a copper loss of 688 watts at full load, and a regulation of 2·77 per cent at unity power factor at full load. The second offer is priced at £44, with an iron loss of 335 watts, a copper loss of 485 watts at full load, and a regulation of 1·9 per cent at unity power factor at full load.

Table 4

Annual running costs	Offer No. 1 (£ per annum)	Offer No. 2 (£ per annum)
Capital charges	3·74	3·74
Iron losses	1·65	3·29
Copper losses	1·39	0·98
Revenue loss	9·4	6·46
Total	16·18	14·47

The table shows that, under the conditions appertaining to this particular case, the revenue loss outweighs all other factors which have to be borne in mind when the transformer is being purchased, and that the low regulation would appear to be the deciding factor in this instance; in consequence of which, and in spite of the high iron losses, it may still be economical to accept transformer offer No. 2.

ACKNOWLEDGMENTS

The author begs to acknowledge the assistance of a number of persons who have helped to carry out the voltage and current tests, and particularly that of Mr. C. C. Bacon, who checked the whole of the calculations.

APPENDIX

Glossary of Symbols

The following terms are employed for the purpose of arriving at the formulæ used in the paper:—

V = Declared voltage of the low-tension distribution system.

R_1 = Minimum value of effective network impedance, in ohms.

[Under normal conditions the voltage at a substation, or point on a distributor, fluctuates owing to a variety of causes; namely, true ohmic impedance of the network, load on the network other than that on the substation or distributor considered, or e.h.t. voltage control for the whole system load generally—and not specifically for the load being considered. In relation to such loads being dealt with, the variations of voltage can equally well be described as being produced by the effective impedance of the network (R). The minimum value of effective network impedance in relation to a low-tension load under review occurs in general when the latter is at its maximum value.]

T = Period of time (taken as 1 year).

T_1 = Period of time for which load exists during time T.

r = Variable-resistance lighting and heating load on the substation or distributor considered.

r_m = Value of r at the maximum-demand period of the individual substation or distributor load considered.

i = Load current corresponding to r, with normal voltage conditions.

I = Load current corresponding to r_m, with normal voltage conditions.

θ_1 = Voltage regulation under the normal voltage conditions at the maximum-demand period at the point considered, expressed as a fraction of the voltage at full load; thus

$$\theta_1 = \frac{IR_1/V}{1\cdot 04 - (IR_1/V)}$$

θ_2 = Voltage regulation at the maximum-demand period at the point considered under conditions where a partial improvement in the regulation is effected such that the voltage at the point fluctuates between 4 per cent in excess of declared voltage at no load and declared voltage at full load, expressed as a fraction of the full-load voltage (i.e. the declared voltage); thus $\theta_2 = I_2R_2/V = 0\cdot 04$.

I_2 = Load current corresponding to r_m with partial improvement in regulation (θ_2).

R_2 = Minimum value of effective network impedance (this includes the regulating gear, if employed to effect the improvement) with regulation θ_2.

θ = Voltage regulation at the maximum-demand period at the point considered, expressed as a fraction of the declared voltage; thus $\theta = IR/V$. The following table gives the value of θ_1, for various values of θ:—

θ	θ_1
+ 4 per cent and declared voltage	0·04
± 4 per cent	0·08333
+ 4 per cent and − 8 per cent . .	0·13043
+ 4 per cent and − 12 per cent . .	0·18181

F_1 = Load factor of the load current at the point considered, expressed as a fraction; thus

$$F_1 = \frac{\int_0^T i\,dt}{I_1 T}$$

F = Actual load factor at point of supply considered; thus

$$F = \frac{\text{Units supplied during time } T}{\text{Max. demand (kW)} \times T}$$

$$N = \frac{\int_0^T i^2 dt}{\int_0^T i\,dt} \times \frac{1}{I} \approx \frac{\text{load factor of the load-current losses}}{\text{load factor of the load current}}$$

N is the same factor as that described in the Overhead Lines Association's Specification for transformers as "the ratio of the areas of the (load current)^2 curve and the load curve drawn to a scale such that at full load the curves coincide." The evaluation of this factor is treated under a separate heading, and values appropriate to the class of load considered are given in Fig. 11, curve B.

A = Correction factor referred to in Fig. 1. The reduction or increase on lighting or heating loads is from 0·79 to 1·1 times that obtained with a pure non-inductive resistance unaffected by temperature. (A is taken as 0·9 throughout.)

m = A factor expressing the diversity of the maximum demand of the load at the point considered. The load occurring on a substation or distributor during the system maximum-demand period is taken as $(1/m) \times$ (Maximum demand) at that point. As an approximate guide,

$$m = \frac{\text{Total of maximum demands on all l.t. substations}}{\text{System maximum demand}}$$

λ = Index defining the law of the symbolic load curve.

Increase in Units

If the voltage at a substation or a point on a distributor is maintained constant at 4 per cent in excess of declared voltage, the power being delivered at any instant will be

$$\frac{1{\cdot}0816V^2}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Under normal conditions, however, at such points the voltage fluctuates, and the power supplied will be reduced by reason of the effective network impedance (R). Taking the minimum value of effective network impedance (R_1), i.e. assuming the minimum loss of power due to this item, the power delivered at any instant will be

$$\frac{1{\cdot}0816V^2r}{(r+R_1)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The difference in power consumption between (1) and (2) is

$$1{\cdot}0816V^2\left[\frac{R}{r(r+R_1)^2}+\frac{R}{(r+R_1)^2}\right]$$

If we insert $(r + R_1)$ in place of r in the first term in the bracket, thus making the loss even less, then the increase in energy supplied over time T is given by

$$2\int_0^T 1{\cdot}0816V^2\frac{R_1}{(r+R_1)^2}dt$$

$$= 2\int_0^T i^2R_1dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Substituting $\theta_1 = R_1/r_m$, and multiplying numerator and denominator by

$$I = \frac{1{\cdot}04V}{(r_m+R_1)} \quad \text{and also} \quad F_1 = \frac{\int_0^T idt}{I_1T}$$

the expression becomes

Increase in energy

$$= 2\times\frac{\int_0^T i^2dt}{\int_0^T idt}\times\frac{1}{I}\times\theta_1\times F_1\times\frac{1{\cdot}0816V^2}{(r_m+R_1)^2}\times T$$

$$= 2N\theta_1 \times \text{(Units supplied under normal conditions)} \quad (4)$$

Using the value of F_1 given above simplifies the solution but has the disadvantage of giving a slightly high result when the equation is being applied with actual values of F. This can be corrected, however, by writing θ in place of θ_1. In order to compensate for the fact that the loads are not of fixed resistance value, the further correction factor A must be applied. Hence the increase in consumption of units is given by

$$2AN\theta \times \text{(Units supplied under normal conditions)} \quad (5)$$

Increase in Maximum Demand

The component of maximum demand of the load being considered reflected on the bulk-supply maximum demand will be $(1/m) \times$ (Maximum demand at point of supply). As a close approximation, if r_m is the ohmic load at the point when the distributor maximum demand occurs, then mr_m will be the ohmic load at the point when the system maximum demand occurs. If the voltage at the substation or the point on the distributor is maintained constant at 4 per cent in excess of declared voltage, the component of maximum demand imposed on the system will amount to

$$\frac{1{\cdot}0816V^2}{mr_m} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

whereas under normal conditions it will amount approximately to

$$\frac{1{\cdot}0816V^2mr_m}{(mr_m+R_1)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

After multiplying numerator and denominator by the maximum demand under normal conditions, and substituting $R_1 = \theta_1 r_m$, the increase in the bulk-supply demand will be

$$\left[\frac{(1+\theta_1)^2}{m}-\frac{m(1+\theta_1)^2}{(m+\theta_1)^2}\right] \times \text{(Maximum demand under normal conditions)} \quad (8)$$

In order to compensate for the fact that the loads are not of fixed resistance, the factor A must again be employed; hence the increase in the bulk-supply demand will be*

$$A\left[\frac{(1+\theta_1)^2}{m}-\frac{m(1+\theta_1)^2}{(m+\theta_1)^2}\right] \times \text{(Maximum demand under normal conditions)} \quad (9)$$

Evaluation of the Factor N

Most domestic lighting and heating distributor loads are of the intermittent type. Long periods of no load occur, interspersed with load periods of relatively steady magnitude which are mainly due to evening lighting. Of the few analytical methods available, those due to the late Prof. Rossander are therefore particularly suited in this case for the determination of the factor N. The following is an extension of these methods, proposed by the author for dealing with intermittent loads.

Assume that over the period T the actual load persists for the time T_1. Then

$$\int_0^{T_1} idt = \int_0^{T_1} I\left(\frac{t}{T_1}\right)^{\lambda}dt \quad . \quad . \quad . \quad . \quad (10)$$

and

$$\int_0^{T_1} i^2dt = \int_0^{T_1} I\left(\frac{t}{T_1}\right)^{2\lambda}dt \quad . \quad . \quad . \quad (11)$$

* In using equations (9), (17), and (21), it should be noted that, while these equations are correct for $m = 1$, as the diversity increases the chance of under-estimating the maximum-demand increment increases because the value of R is indefinite at loads other than the maximum. The maximum-demand increment for increasing diversity, however, falls off so rapidly (see Fig. 10) that the importance of the factor, and therefore of the error, decreases. In addition, where the maximum-demand increase by equation (9) is under-estimated the units increase by equation (5) is normally also under-estimated to sueh a degree as to render the use of the former equation entirely satisfactory.

From (10),

$$F = \frac{\int_0^{T_1} I\left(\frac{t}{T_1}\right)^{\lambda} dt}{IT}$$

Hence

$$\lambda + 1 = \frac{T_1}{T} \times \frac{1}{F}$$

And therefore,

$$N = \frac{\int_0^{T_1} i^2 dt}{\int_0^{T_1} i dt} \times \frac{1}{I} = \frac{(T_1/T)}{2(T_1/T) - F} \quad . \quad . \quad (12)$$

The above evaluation of N is true between the limits $F = 0$ and $F = (T_1/T)$.

Values for N are plotted in Fig. 11 for the case of a pure lighting load assuming that it exists for 25 per cent of the year, and for a lighting and heating load existing for 50 per cent of the year. For comparative purposes further curves are added for mixed system loads, using Rossander's methods as developed by Ekström* for the latter class of load having minimum values amounting to 1 per cent and 5 per cent of full load respectively. Further curves and points, all derived independently by other investigators, are also given for comparison.

The following points are of particular interest:—

(*a*) When Rossander's methods are applied to normal system loads in this country the values of N obtained are almost the same as those derived from Bolton's equation.

(*b*) The two factors N proposed by the Overhead Lines Association for conditions where T_1/T is somewhat greater than the value considered here, lie in correct relationship with curves A and B, Fig. 11.

(*c*) The two points derived by the author for loads comprising mainly lighting, also lie in correct relationship.

(*d*) The values of N given by curve B, Fig. 11, can therefore be said to be reasonably accurate, and can be employed with safety for the class of load considered.

Finally, whatever analytical method is used for evaluating N, the ratio of the load period to the total time (i.e. T_1/T) is of predominating importance; and, for any given load factor, the lower the ratio T_1/T is, the higher N becomes.

Additional Formulæ for Supply at Constant Voltage

If the voltage at the substation or point on the distributor is maintained constant at the declared value instead of at the normal fluctuating conditions, the increase in the power being delivered at any instant is given by

$$\frac{V^2}{r} - \frac{1 \cdot 0816 V^2 r}{(r + R_1)^2} \quad . \quad . \quad . \quad . \quad (13)$$

and, employing similar methods to those already described, the increase in the energy supplied is found to be

$$\frac{2}{1 \cdot 0816}\int_0^T \frac{1 \cdot 0816 V^2 R_1}{(r + R_1)^2} dt - \frac{0 \cdot 0816}{1 \cdot 0816}\int_0^T \frac{1 \cdot 0816 V^2 r}{(r + R_1)^2} dt \quad (14)$$

$$= A(1 \cdot 8491 N\theta - 0 \cdot 0754)$$
$$\times \text{(Units supplied under normal conditions)} \quad (15)$$

Also, the increase in the bulk-supply demand will be

$$\frac{V^2}{mr_m} - \frac{1 \cdot 0816 V^2 mr_m}{(mr_m + R_1)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

$$= A\left[\frac{(1 + \theta_1)^2}{1 \cdot 0816 m} - \frac{m(1 + \theta_1)^2}{(m + \theta_1)^2}\right]$$
$$\times \text{(Maximum demand under normal conditions)} \quad (17)$$

Additional Formulæ for Supply at Improved Voltage, Fluctuating only between + 4 per cent and Declared Voltage

If the voltage at the substation or point on the distributor is allowed to fluctuate between 4 per cent in excess of declared voltage at no load and declared voltage at full load, instead of the normal fluctuating conditions (the total actual fluctuation assumed to be greater than the former), the increase in the power being delivered at any instant is

$$\frac{1 \cdot 0816 V^2 r}{(r + R_2)^2} - \frac{1 \cdot 0816 V^2 r}{(r + R_1)^2} \quad . \quad . \quad . \quad (18)$$

Employing similar methods to those already described, the increase in energy is found to be

$$2\int_0^T \frac{1 \cdot 0816 V^2 R_1}{(r + R_1)^2} dt - 2\int \frac{1 \cdot 0816 V^2 R_2}{(r + R_2)^2} dt$$

$= 2AN[(\theta - \theta_2) \times$ (Maximum demand of supply under improved conditions)/(Maximum demand of supply under normal conditions)]

$\times$ (Units supplied under normal conditions) . . (19)

Also, the increase in the bulk-supply demand will be

$$\frac{1 \cdot 0816 V^2 mr_m}{(mr_m + R_2)^2} - \frac{1 \cdot 0816 V^2 mr_m}{(mr_m + R_1)^2} \quad . \quad . \quad . \quad . \quad . \quad (20)$$

$$= A\left[\frac{m(1 + \theta_1)^2}{(m + \theta_2)^2} - \frac{m(1 + \theta_1)^2}{(m + \theta_1)^2}\right]$$
$$\times \text{(Maximum demand under normal conditions)} \quad (21)$$

* V. EKSTRÖM: "Calculation of Load Losses."

[The discussion on this paper will be found on pages 48 and 57.]

DISCUSSION BEFORE THE TRANSMISSION SECTION, 11TH DECEMBER, 1935, ON THE PAPERS BY MR. NAYLOR (SEE PAGE 33) AND MESSRS. WEDMORE AND FLIGHT (SEE VOL. 76, PAGE 685)

Mr. C. F. Mounsdon: Dealing first with the paper by Messrs. Wedmore and Flight, the business of the supply engineer is to give a good supply, no matter by what means and at what cost, within reason. If we are able to provide a good supply at 0·6d. per unit, whereas by selling at 0·5d. we can only give a bad supply, there can be no question that our price must be 0·6d. Our object is a great increase in load, and this can only be obtained and retained by an efficient supply. This may mean larger mains, but meanwhile we have balancers, tail-end boosters, and regulators. Balancers are one of the cheapest methods of improving regulation, and I have many sections of distribution mains where they are indispensable. We need the statutory $\pm$ 6 per cent limit of voltage variation for occasional protection against aggression, but apart from this, it is our business to forget about it and to keep our regulation within very much finer limits.

I think that one of the main factors that has deterred supply undertakings from keeping the voltage up over the peak period, where general regulation is not adopted and full voltage at peak periods involves high voltage at times of light load, has been the bugbear of shortening the life of lamps, and it is in that direction that something could be done. There is a fetish that a lamp ought to last 1 000 hours, but if we put the normal life of the lamp at 500 hours, and manufacturers halve the cost by virtue of increased sales and wider tolerances, we shall be in the same position as now so far as the cost of lamp renewals is concerned but in a very much better position as regards voltage regulation.

Turning to Mr. Naylor's paper, Fig. 10, curve (*b*), shows a diversity factor of 1·8, but the author states (col. 1, page 42) that at the time of peak load on the system the load on this particular substation is 0·55 full load. That is the time when the voltage regulation on the substation will affect the peak load, and therefore if we take the increase of load due to raising the voltage at that time and deal with it as a diversity factor of 1 we get a somewhat different result; we get an increase of £13 as against the figure of £8 shown in Table 3. The point on which I should like information is why there is a difference in calculating for a diversity factor of 1·8, as here, and a diversity factor of 1 as at the time of the system peak-load.

With reference to Table 3, the figure of £14 increase in revenue for a voltage regulation of $\pm$ 4 per cent should, I think, read £17. Apart from this, however, I would mention that in my own supply area this case would have a diversity factor of 1 instead of 1·6 at the time of system peak load, because with most of my substations the peaks occur all at the same time, so that each substation practically gives its peak at the time of the system peak. A diversity factor of 1 gives a loss of profit of £11 instead of an increase of profit of £17 (or the author's £14), and if we add the capitalized cost of a regulator, which the author gives as £12 per annum, we have an additional cost of £23. On the load factor of 25 per cent this means an additional cost of only 0·027d. per unit. In view of this it seems to me that we must look at the broad issue, and, if it costs so little more to give a good supply, then we must go to that expense.

Mr. H. Nimmo: The title of the paper by Messrs. Wedmore and Flight might with advantage have been "Voltage variation at the terminals of the consuming devices"; which is, I presume, what the authors mean by the title they have adopted.

The variation which is allowed by the Commissioners' regulations is in a state of some confusion at the moment, because all low-voltage supplies given up to the 15th January, 1934, are subject to a variation of 4 per cent above and 4 per cent below the declared voltage, while all supplies given since that date are subject to a variation of 6 per cent above and 6 per cent below. For high-voltage supplies, prior to the 15th January, 1934, a variation of $12\frac{1}{2}$ per cent above the declared minimum voltage was allowed, but under the 1934 regulations the variation is $\pm$ 6 per cent. The majority of engineers favour $\pm$ 6 per cent, and under the Commissioners' revised regulations, the draft of which is about to be sent out for criticism, all supplies will probably be subject to a variation of $\pm$ 6 per cent of the declared voltage.

After studying the paper by Messrs. Wedmore and Flight, however, I am not at all convinced that equal tolerances of 6 per cent above and 6 per cent below can be justified. The supplier's concern is with the voltage at the supply terminals, but surely allowance ought to be made for the inevitable voltage-drop in the consumer's installation. It is suggested in the paper that this allowance should be 2 per cent, and it is also pointed out that if an average voltage of 2 per cent above the declared voltage is maintained at the supply terminals the consumer will get the best service, and incidentally the supplier will obtain the little extra revenue. I agree with the authors that there is no justification for equal tolerances. I would, however, suggest that the tolerances ought to be confined to rather closer limits than they have suggested; my figures would be + 6 per cent and − 4 per cent, the extra 2 per cent being to cover the voltage-drop in the consumer's installation.

In conclusion, I should like the authors to give a little further information with regard to their statement on page 699: "It would appear that improved performance could be obtained under regulations allowing even a larger range than + 6 to − 6 per cent if the departure of average could be tied at the same time." I ask this because in the paragraph just above the authors suggest that the supply authorities should aim to secure that the average voltage at the consuming points should not vary from a standard value by more than 2 per cent.

Mr. J. A. Sumner: The papers are typical of the fairly recent movement to bring distribution and transmission on to the plane of a science. The more this art becomes a science the more will both the consumers and the industry itself benefit.

I am not entirely in agreement with the thesis which

is contained in both the papers, and particularly in that by Mr. Naylor, that low voltage causes a loss of revenue. It is a fact that when low voltage occurs people very often put in a bigger lamp, which they forget to remove when the voltage returns to normal. I should hardly think that, in total, low voltage causes a loss of revenue; on the contrary it probably causes an improvement. The chief factor, however, is the psychological one; if people have to put up with a voltage-drop of 10, 15, and in some cases 20 per cent, they will lose their enthusiasm for electricity, and it certainly will not advance at the rate which will make it a complete instead of a partial service to the community.

Dealing with Mr. Naylor's paper; the author makes the important point that regulation becomes less important as the charge per unit is reduced. On page 41 he refers to a particular case, and shows us the financial effect of having a voltage regulator in a particular rural substation. I am not quite sure, however, that the case is apt. He is dealing there with a total consumption of roughly 70 000 units, only one-third of which, 23 118 units, are for lighting at 7·2d. per unit, so that one-third of those units account for 75 per cent of the total income. This is surely a very particular case, and probably rather over-stresses the author's point, because few undertakings will continue to charge 7·2d. per unit for lighting over the period of 3 or 4 years which must be assumed in a financial calculation of this nature. I have reason to think that 3 years from now in the case quoted by Mr. Naylor the figure of 7·2d. may be down to 5·2d. Further, if the 2-part tariff is made much more attractive and is adopted by the consumer as it will be in the particular case quoted, then all the units consumed will be charged at 1d. or less. In the latter event, instead of the annual saving of £76 given by the author as the increased profit due to regulation, the figure will be £13. The case should really be based on a profit of £18, i.e. £26 less £8 capital charges, rather than on the £76 which the author mentions.

I agree with the author that, when one is purchasing a transformer, regulation is more important to consider than copper or iron losses. I was very interested in the method which he showed whereby the iron in a transformer was arranged so as to give inherent voltage regulation, and I think it would be better to make use of this principle rather than to follow the present complicated arrangements involved in automatic voltage regulators.

There are two points in the paper on which I am not at all clear. Firstly, on page 41 the author mentions a 60-kVA transformer; was this made to order? It is of a non-standard size, and I should like to know whether more money had to be paid for it on this account. If so, the author might have bought a 100-kVA or 50-kVA transformer of standard size, and thus achieved an annual financial saving. Secondly, I should appreciate some further explanation of the meaning of the last paragraph on page 43.

Mr. W. Fennell: I should like to refer to the factor N, defined on page 45 of Mr. Naylor's paper. The value of this factor, which represents the difference between the area of a current curve and the area of the similar current-squared curve taken to such a scale that the maximum loads coincide, is beginning to be required in connection with calculations of the running costs of indirect bulk supplies on the grid system. Under Schedule 3 of the Act of 1926, transmission costs are charged to the unfortunate undertaking that does not get a supply direct from the grid, and one of these costs is the I^2R losses in the line and in special transformers. As an example showing how much the I^2R losses may vary with the shape of the load curve, we may draw two extreme curves for getting a load factor of, say, 50 per cent. For one extreme we can take a 100 per cent load for half the time, and for the other we can take a load of half the maximum for all the time (except for a very short period, during which the full load will exist, which is negligible in the calculation). The areas under the two curves are the same, but the I^2R losses in the former case are exactly twice what they would be in the latter.

Mr. D. J. Bolton: I want to speak more particularly on the paper by Mr. Naylor, which is interesting because it deals with borderline science. It covers two areas, the area of engineering and the area of psychology, and I think the author should have made a little more of the one, even if he had to crowd the other out. There are two questions: What would a consumer do in such and such circumstances, and what would the results of that action be? The results of the action are engineering and economic problems, but the action itself is psychological.

We can analyse the consumption by and control of domestic apparatus, in particular, into two definite groups. There is the type of control which is planned out beforehand, the apparatus being switched on according to some definite programme, and on the other hand there is the type which aims at a certain result and takes no particular notice of declared voltages or apparatus wattages. To the average householder the expressions "230 volts" and "25 watts" convey little or nothing; his lamps are chosen to give a certain effect. The second class of consumption is not affected by steady voltage departures, i.e. departures where the average voltage is either below or above the declared value, and this second class includes a very considerable amount of domestic consumption. It includes, for example, all thermostatically-controlled consumption, where the appliance is automatically connected for a longer or a shorter period according as the voltage is low or high. In this second group are also included such things as irons, which are normally switched on for, say, 5 minutes before they are used; if the voltage is habitually low, that 5 minutes becomes 7. We ought to form an estimate of how the consumption is divided between the two groups I have mentioned.

The author quotes a formula given by me, and although I was not the originator of it I should like to say a word or two in its favour. Mr. Beard showed many years ago that, say, a 25 per cent load factor may be the result of full load for one-quarter of the time or one-quarter load for the full time, the relation between the load and the losses in one case being F and in the other F^2; in other words, the loss in an actual case will be somewhere between the two limits F and F^2. The formula which I use is $0 \cdot 3F + 0 \cdot 7F^2$, and the one the author uses is based on work carried out on the Continent by the late Prof. Rossander. It is much more compli-

cated than mine, and results in very similar figures, provided that F is the load factor during the connection period.

It is extremely difficult, when people are purchasing apparatus, to get them to take any notice of economic factors other than the first cost of the plant, and in order to persuade them to do so it is preferable to have a simple rather than a complicated formula. To take actual figures, consider the case of a 1-kW full-load copper loss on a 10 per cent load factor. If this figure of 10 per cent were due to continuous connection to the supply system, the mean copper loss by the above formula would be 0·037 kW. If this case occurred in works connected for 8 hours a day, the load factor during the 8 hours being 30 per cent, so that one got the same average of 10 per cent over the year, the copper loss would be 0·051 kW.

Mr. E. T. Norris: I have one comment to make on the paper by Messrs. Wedmore and Flight. A considerable part of the paper is devoted to a method of analysing and weighting daily voltage charts in order to arrive at some basis of valuation. The authors' method is admirable where one is considering the life of electrical apparatus, but if one is considering the effect of voltage variations on the customer, frequently a much more important matter, then the weighting should be very much heavier. This aspect reminds me of a personal experience of a few years ago, when after selling a house I found that the first thing the newcomers had done was to remove the electric cooker. When I tried to find out why, the housewife said "I am not having an electric cooker again; I had one before and it took ages to cook breakfast with it." Presumably the voltage had been so bad that it had taken her a very long while to cook the breakfast with an electric cooker as compared with a gas cooker. It may be that that voltage had been within 1 per cent of normal for the whole of the rest of the day, but the authors' weighting curve would not have been applicable in such a case.

Mr. Naylor's paper is distinctive in that it puts forward a case for voltage regulators as part of the normal layout of a supply system, whereas in the past voltage regulators have been considered in this country only when the supply engineer has been in difficulties. Mr. Naylor deals with voltage regulators from the purely financial point of view of increase in revenue, but they have two equally important uses, namely (*a*) for improving the service provided by electricity, and (*b*) for reducing the cost of distribution and transmission. In view of the very large proportion that the cost of lines and substations bears to the total cost of distribution, it is easy to show a good economic case for (*b*). For example, in a paper recently read before the Electrical Power Engineers' Association at Birmingham Mr. A. C. MacQueen describes in the following terms a typical low-tension feeder problem: "On a 4-core 0·5-sq. in. feeder 300 yards in length, carrying 75 per cent full load, the voltage drop at the feeding point would be approximately 13 volts between phases. An expenditure of £800 on l.t. cables would only reduce this drop to 6·5 volts, whereas a compounded regulator costing approximately £200 would not only entirely eliminate the voltage drop on the feeder, but could be arranged to compensate for part of the voltage drop on the distribution as the load increased." The chief point is that the use of regulators will permit the rating of cables, lines, and substations, to be greatly increased—even up to the full thermal limit. Messrs. Kidd and Carr* state, as axiomatic, that without voltage regulators it is not possible to load cables and transmission lines thermally. The increased rating can be utilized either to reduce the cost of the feeders or to increase their capacity.

Turning to Table 4, which gives details of two transformers, one with high and the other with low copper losses, I think it would be more economical to accept Offer No. 1 and put in a voltage regulator. Even if that regulator were put in entirely for the purpose of reducing the extra regulation of the transformer, it would still show a substantial economic advantage, the total annual cost being £12·98 instead of £16·18. If the regulator had been provided already for voltage-regulation purposes, the annual cost would be further reduced to £7·36.

Mr. W. E. M. Ayres: Both papers are interesting in that they present an old problem from new, and perhaps unusual, points of view. Both papers mention a variation in network impedance with load. In the paper by Messrs. Wedmore and Flight this is called a "branching factor." This aspect requires more consideration.

As illustrated, showing a reduced network impedance with increased load, the argument would inevitably lead to reduced voltage variation, yet the authors still find voltage maintenance by corrective devices sound commercial policy. Reduced network impedance does not invariably result from increased load, and I could point to quite contrary conditions. It all depends on the amount of feeder resistance to the centre of gravity of the load. This is shown in Tables 1 and 2 and Fig. 4 (cols. A and C) of Mr. Naylor's paper, where the loads are dissimilar but the network impedance is the same because the distribution is identical. In Fig. 4, col. D, the proportion from the nearer substations is very much smaller, and Table 2 shows an increase in effective network impedance because the centre of load is farther from the power source.

With regard to the branching factor, which incidentally is not fully explained, it is not mathematically credible that the paralleling-in of more load reduces the effective impedance. If, however, for a certain load the number of paths is increased, then there will be a reduced impedance. The load itself must be neglected in estimating on this basis, but one can take the voltage-drop as proportional to the line losses, which are a product of the current density squared by the weight of conductor. Obviously doubling the number of paths will halve the density, which reduces the loss per unit weight to one-quarter; but the weight will be doubled, and hence the loss and effective impedance are halved.

Both papers assume that the motor load is unaffected by voltage-drop. Except for efficiency difference this may be true for the watts consumption, but it must not be forgotten that when the voltage falls the motor takes more current and may become overheated. The overload capacity also is proportional to the square of the terminal

* *Journal I.E.E.*, 1934, vol. 74, p. 285.

voltage. For these reasons it has been found necessary to install voltage regulators for motor loads.

Mr. Naylor shows that increased revenue may pay the whole capital cost of the regulating device in 2 years. True, his figures are calculated on a certain basis which may not always apply, but they agree with a large amount of my own experience.

One must not forget the effect of good service in these voltage-variation problems. The value of good service cannot be estimated mathematically, except perhaps by the method of statistics used in the paper by Messrs. Wedmore and Flight, but the increase in load, particularly cooker load, arising from good voltage conditions is enormous compared with the cost of the regulating plant.

Messrs. Wedmore and Flight mention (page 698) the use of series resistance at the source; neglecting the question of losses, how do they expect to cope with the over-voltage on light loads? If the longer feeders are within permissible limits, which they should be, why waste energy in resistances to make the shorter feeders better than they need be?

Mr. A. R. Cowell: I shall confine my remarks to the paper by Mr. Naylor.

The author points out that supply undertakings can obtain increased revenue by maintaining the voltage at the substation terminals at 4 per cent above the declared pressure. Besides bringing in extra revenue to the supply undertaking, the maintenance of a steady voltage such as this also begets satisfied consumers; giving the consumer constant cooking and heating results, better lighting, etc. This is of the utmost importance to the supply undertaking, as a satisfied consumer is the best advertisement that the undertaking can have. Good voltage regulation is also of great importance in industrial applications, particularly where electrically-heated kilns and annealing furnaces and the like are employed, in which close temperature control is usually required over long periods of time. In such applications, if appreciable voltage variation occurs at the consumer's terminals, it is impossible to maintain the temperature within the required close limits, the temperature variations being intensified owing to the fact that the heating effect varies as the square of the voltage.

I therefore suggest that the voltage at the substation terminals should be maintained at the declared value at no load, and be made to rise with load to 4 per cent above the declared voltage at full load. Voltage regulators can be made to fulfil this condition easily and cheaply by "compounding" the voltage relay, i.e. by providing "line-drop compensation." A large number of such regulators are in use at the present time. If such regulators were installed, the voltage at the majority of the consumer's terminals would be maintained at a constant value, approximating to the declared voltage, whatever the loading conditions. This would be advantageous, because it is more important to keep the voltage constant at the consumer's terminals than at the substation terminals.

The argument that the author will probably bring against this suggestion is that, if it was carried out, a smaller extra revenue would be obtained by the supply undertaking than if the voltage at the substation terminals was maintained at a steady value of 4 per cent above the declared pressure. The difference, however, would be small; because, under the conditions that I have just specified, it would only be at times of light loading, i.e. when very few units were being sold, that the voltage at the substation terminals would be as low as the declared voltage. On the other hand, at times of full load, when the bulk of the units were being sold, the voltage would be up to 4 per cent above the declared pressure. Consequently it would appear that, so far as extra revenue is concerned, the conditions I have just outlined approximate to the conditions specified by the author.

Finally, on page 42, the author states that in making his calculations he has neglected the cost of the extra losses incurred by the regulator, thus assuming that, in the process of regulating the voltage at the substation terminals, extra losses must necessarily occur. This is, of course, not so, as extra losses will only occur if a voltage regulator is installed at the substation to work in conjunction with an existing static step-down transformer. If, on the other hand, as is more usual and convenient, the step-down transformer at the substation is equipped with fully automatic on-load tap-changing gear, then any reasonable voltage can be maintained at the substation terminals without extra losses being incurred; and in fact a saving in losses can actually be effected by fitting the tap-changing gear to the high-tension side of the transformer.

Mr. F. La T. Budgett: I believe that with a.c. watt-hour-meters, if the consumption of the apparatus is reduced on account of low voltage, the amount which the consumer pays is also reduced in the same proportion. On the other hand, with d.c. ampere-hour meters under similar conditions the consumer pays more than he should, because the meter only records the reduction in ampere-hours and not the greater reduction in watt-hours which the consumer receives.

Mr. Mounsdon suggested a 500-hour life for a lamp of half the price. This idea has been adopted in the United States, where the standard price of a 1 000-hour lamp is 22 cents but a 10-cent lamp with a guaranteed life of 500 hours is also on the market.

With regard to voltage variation at consumer's terminals as compared with that at apparatus terminals, this is a serious problem for American power companies, particularly where the consumer has to pay for the entrance wires from the roof of the house down to the cellar where the meter is fixed. The difficulty is that if these wires are at first installed for small loads and then the consumer wants to add a cooker, it may cost him £10 to change the outside wiring and put in a larger main switch. A great deal of propaganda has been necessary recently to persuade consumers to put in wire and conduit of ample size to start with, designed to take any reasonable load which may later be required.

Coming to the difficult problem presented by the very long rural line, if one installs voltage regulators with the idea of boosting the voltage at the near end, the voltage supplied to nearby consumers is too high while at the same time that at the far end is too low. The obvious way is to put in regulators at two or three points along the line, a fairly expensive method. Another solution

is to use a series capacitor to neutralize the considerable reactance of an overhead line. The capacitance voltage-rise of this device automatically increases in proportion to the load in the same way that the reactance drop of the line does. When I was last associated with the series-capacitor method it was still in an experimental stage. One difficulty was that it was necessary to provide certain protective devices which formed a very high proportion of the cost of an equipment for a circuit of small kVA rating. The cost of these protective devices was said to be about the same for a line of relatively much larger kVA rating and higher voltage, so that the apparatus would be more practicable from a financial standpoint in the latter case.

Mr. H. W. Grimmitt: In the figures given by Messrs. Wedmore and Flight statutory voltage variation is in all cases exceeded, but I am perfectly certain that the position with regard to voltage variation is not nearly so bad as one would imagine from the discussion and from the authors' charts. The problem is, how long can one give a supply the voltage of which is above the prescribed limit, without harm to the consumer or to the revenue of the undertaker?

I am inclined to disagree with what Mr. Naylor says in the second paragraph of his Introduction, namely that excessive voltage variation is not a problem for the engineer. The general practice in this country has been to install cables and overhead lines of larger rating than is normally required, and consequently voltage-variation trouble has not been experienced here to the extent it has been on the Continent and in America. There, where they budgeted only for lighting load, voltage regulators are now the general rule, but they were not planned in advance. It can be shown, as the author pointed out in introducing his paper, that if one installs a voltage regulator on a network, and especially an overhead network, one can increase its capacity. If the network is governed purely by regulation, the units sold can be approximately doubled. Mr. Norris goes a little farther and suggests that with regulation one can operate the network up to the heating limit. This is rather the extreme, as before this state is reached Kelvin's law has to be taken into account.

The author chose a very difficult problem when he endeavoured to show that a gain in revenue is obtainable by working in the upper limits of the prescribed regulations. He could, however, very easily have shown a great saving in regulation owing to the increased capacity of the network. Again, previous speakers have talked for the most part about reducing the cost of transmission. With a regulator one can roughly double the capacity of the network, but one cannot halve the cost of transmission.

Mr. F. C. Knowles: I should like to refer to the tapping type of recorder employed by Messrs. Wedmore and Flight. It has been suggested that a method of getting the curves straight away, without the labour involved by the authors' method, would be that instead of the tapping pointer coming down on a chart it should come down on a contact which would energize a little electrical counter. The contacts would be spaced 1 per cent apart, and contact would be made every minute. Each indicator would give an integration of volt-minutes so that after a given period of time one could read the indicators and plot the curves straight away.

Another possible way of obtaining a rough equivalent of the information given by the authors' curves is a combination of their apparatus with a method which was first adopted in France and Germany, namely to use a volt-hour meter over a definite period of time and then compute the average voltage over that time. The chart-recording voltmeter would at the same time enable the observer to spot the peak periods.

Mr. W. Fordham Cooper (*communicated*): I should like to refer to a statistical study which I made in 1926,* on similar lines to those described in Section I of the paper by Messrs. Wedmore and Flight. So that the investigation could be made to apply to the aggregate load of a large number of consumers, in my case the total load on a substation or feeder was studied instead of the voltage variation. Complete statistical data were not available, but from a study of the daily load curves and by a line of argument rather the inverse of that used in Fig. 3 of the present paper it was inferred that the load variation would be given by a frequency curve essentially similar to that given for voltage variation in Fig. 2. The two are obviously interchangeable, because of the relation $v = IR$; or, by taking moments in the manner described below, Fig. 23 is immediately obtained. Although there were not then sufficient data from which to plot the frequency curve, it was possible to infer its general form; for example, certain data were obtained as to the possibility of deviations beyond various limits. For a normal curve this possibility would have been represented by an expression of the form $pn + q\sqrt{n}$. It was found, however, to agree with great accuracy with the formula $pn + q\sqrt{(n - m)}$ which had previously been found to apply empirically to "skew" distributions such as that given in Fig. 3 of the paper by Messrs. Wedmore and Flight. Since then, further investigations by almost exactly the same method as that used by the authors have completely verified the theoretical conclusion of my original investigation.

The last part of their paper, which deals with voltage regulation, is not sufficiently detailed, and in particular the effect of the voltage-drop in the neutral of a 3-phase 4-wire system is not considered. In my experience this has often been the dominating feature in suburban and rural areas where cookers and large radiators or water heaters are used. The method which I used for investigating this point was as follows.

To obtain compliance with the Electricity Supply Regulations current at the time the investigation was made, it was decided to see what steps could be taken to ensure that except in abnormal circumstances the voltage-drop should not exceed $3\frac{1}{2}$ per cent in the mains and $\frac{1}{2}$ per cent in the services, so that the total drop at the consumers' terminals should not exceed 4 per cent. When making such an investigation it is clear that the effect of out-of-balance current in the neutral conductor of a 3-phase 4-wire system must be considered, and the variation taken must be the phase-to-neutral variation on the worst phase. This effect of the neutral drop (or deflection) may be so serious as to be the predomi-

* Described in an informal lecture to the Junior Institution of Engineers, April, 1927.

nating effect in residential and rural areas. The use of a large electric cooker at the end of a long feeder will sometimes cause serious over-voltage at the terminals of neighbouring consumers, who are supplied from the other phases. The occurrence of a particularly troublesome case of this description was an important factor in the decision to make this investigation.

It is easily proved that if the currents I_a, I_b, and I_c in the three phases are at approximately the same power factor, and v is the voltage-drop for a balanced load of I_c amps. in each phase, then the actual voltage variation (fall or rise) in phase c is given approximately by

$$\delta V_c = v\left[1 + k_1\left(1 - \frac{I_a + I_b}{2I_c}\right)\right] \quad . \quad . \quad (1)$$

$$= vk_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where

$$k_1 = \frac{\text{impedance of neutral}}{\text{impedance of phase wire}}$$

The following is an example:—

Phase	Amperes	Open-circuit volts	Volts across load	
			Calculated	Measured
a	36	245	236	235
b	71	245	208	207·5
c	8	245	260*	256·8*

* Due to rise of voltage.

These figures were worked out to check whether a section of irregularly-spaced overhead line in the supply to a large estate produced sufficient effect to upset calculations.

A simpler form of this formula has since been used by A. W. Crompton.* When dealing with cable systems having small reactance we can define k_1 sufficiently accurately as

$$k_1 = \frac{\text{area of cross-section of phase core}}{\text{area of cross-section of neutral}}$$

This formula can be simply applied to the case of a number of loads scattered along the length of a cable by making use of the principle of moments. For a single load on a uniform conductor,

$$v = Irl$$

where l is the length of a conductor and r is the resistance per unit length; and, for a distributed load,

$$v = r\Sigma Il \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Practical calculations are greatly simplified by expressing the moment of the load, Il, as "kW-yards of 0·1-sq. in. cable" (all cable lengths readily reduce to this basis, the resistances being inversely proportional to the section and being replaced by a constant k_3), on the assumption that the voltage variation is reasonably small. As many loads are of the resistance type, such an assumption does not lead to great inaccuracy. Equation (2) can then be written in the form

$$\delta V_c = k_2 k_3 \text{ (Sum of kW-yards)} \quad . \quad . \quad . \quad (4)$$

* *Electrical Power Engineer*, 1930, vol. 12, p. 193.

In evaluating k_2 for this case, I_a, I_b, and I_c in equation (1) are also replaced by the equivalent values in kW-yards. The first step in an investigation is to sum the kW-yards outwards from the substation terminals. In this manner it is easy to take account of branching networks. Where a cross-connection occurs, an approximation is usually sufficient, but by analogy with mechanical problems it is often possible to obtain an exact solution by taking moments about the two ends, as for a beam. Simplification can also be obtained by dealing with loads in sections and superimposing the results—this is permissible as the equations are linear. In my own investigation the effect of diversity factor on the maximum demand and the neutral drop was estimated by a statistical analysis, as mentioned above, and typical values of k_2 were obtained for various classes of loads.

The difficulty of making reasonable estimates of probable loading is not so great as might be suspected. For example, J. M. Donaldson* shows that the load per 1 000 yards is almost the same for very different conditions. He quotes the following examples:—

	Consumers per 1 000 yards	Maximum demand	
		Per consumer	Total per 1 000 yards
Small houses close together, lighting only	145	120 watts	18 kW
Large houses spread out, lighting only	40	400 watts	16 kW

The ultimate unit of supply is the individual consumer, and from a technical point of view there is nothing to distinguish between a consumer at the end of a special branch distributor and a consumer whose house stands in its own grounds and is supplied by a long service cable.

When carrying out the investigation mentioned above I also made a study of the effects on voltage balance of various methods of splitting up large domestic loads between the phases. I found that the following represented average conditions, when suitably split up:—

Connected load	Normal maximum demand	E.D.
kW	kW	kW
8	5	20
12	6	
17	8	25
22	12	

"E.D." is the effective balanced 3-phase load which will give the same voltage-drop as that on the worst phase for the actual unbalanced load. This is less than the drop for the whole maximum demand taken on one phase, with a 2-core service; e.g. for the 22-kW connected load, 8 kW on each phase produces better regulation than 12 kW on one phase only. By such studies, schedules were drawn up to ensure that service and

* *Journal I.E.E.*, 1929, vol. 67, p. 619.

branch feeder sizes to individual consumers could be fixed as a matter of routine in such a way that the limits of regulation assumed would rarely be exceeded. The values recorded took the form of maximum kW-yards of load allowable for each size of the 2-, 3-, and 4-core cable.

It is easily shown that, for similar power factor on all phases and only non-inductive resistance in the cables

$$\delta V_c = v\left\{\left[1 + k_1\left(1 - \frac{I_a + I_b}{2I_c}\right)\right] + jk_1\frac{\sqrt{3}}{2}\left(\frac{I_a - I_b}{I_c}\right)\right\}$$

When the power factor of the load is fairly high, as is usual in residential areas, the imaginary term can be omitted without serious inaccuracy, and this equation then reduces to equation (1), and can be extended as a first approximation to moderately reactive lines.

Mr. F. S. Naylor (*in reply*): In view of the fact that almost every speaker has dealt with a different aspect of the paper, it will be better for me to reply to the speakers individually, the various points being dealt with in the order in which they have been raised.

Mr. Mounsdon's way of looking at the problem of regulation appears to be very admirable, and there is probably no doubt that it would be better to give a good supply at 0·6d. per unit rather than a bad supply at 0·5d. per unit. I entirely agree with his remarks as to the normal life of a lamp. A big percentage of the lamps in use at the present time probably give a quite unsatisfactory light, and by correctly maintaining the supply voltage obsolete lamps would quickly be discarded and more satisfactory lighting obtained owing to their more frequent replacement.

Mr. Mounsdon suggests a method of calculating the increase in kVA on the substation in the example given on page 42 of the paper. I am afraid that his method is incorrect. To explain the difference between the correct method and the one he puts forward, reference must be made to equation (9) on page 46, from which the curves in Fig. 10 are derived. By making the calculation in the way Mr. Mounsdon suggests, he assumes that the full 8 per cent regulation occurs at 0·55 load; this is not the case. If he desires to employ his method he must ascertain the substation regulation at the time of the system peak. The load on the substation at this period is 50/1·8 kVA, i.e. 27·8 kVA. The regulation (roughly proportional to the load) at this time will be 27·8/50 of 8 per cent (=4·45 per cent). This figure when checked on the load and voltage curves is found to be approximately correct. Referring now to Fig. 10, with a diversity of 1·0 and a regulation of 4·45 per cent, the increase in maximum demand will be 8·6 per cent of 27·8 kVA, i.e. 2·39 kVA, which is actually slightly less than the figure of 2·5 kVA obtained by my method. The latter is simpler and ensures no underestimation of the increase in the kVA maximum demand on the system by increasing the voltage.

It would appear that Mr. Mounsdon has arrived at a wrong conclusion by adopting for his particular case my figure of 0·6d. per unit. Obviously, if he had no diversity on his system, it would necessitate a relatively high load factor before his undertaking could afford to supply electricity at this low unit rate. In addition, rarely, if ever, are all consumers on a distributor supplied on the same tariff, and I suggest that it would be better for him to take an actual case on his undertaking, with the appropriate tariffs, and ascertain to his own satisfaction that there is, in fact, a very big potential increase in revenue by voltage improvement.

In reply to Mr. Sumner, as stated in my preliminary remarks in presenting the paper I believe that the transmission, distribution, and utilization, of electricity have in the past been somewhat neglected for other subjects which lend themselves more readily to scientific investigation. There is no doubt that the subject of the relation between voltage regulation and revenue is a difficult one, but this is no reason for neglecting or avoiding it, and it is hoped that the more we apply scientific methods to these and allied subjects, the more will both consumers and the industry benefit, as Mr. Sumner suggests.

His suggestion that on the occurrence of low voltage it is the custom of most people immediately to substitute new and bigger lamps is not in accordance with my experience; in fact, most lamps have a far longer life than is desirable. His argument might apply in an extreme case, but my paper does not attempt to deal with such extremes and is purposely confined to small voltage-regulations such as $\pm$ 4 per cent, where it can be said, with a fair degree of certainty, that the principle of revenue loss applies.

Dealing with the points Mr. Sumner raises in connection with the example on page 41, it is probable that this may be a particular case in his own experience. I have purposely, however, adhered to the high price per unit because it is the rule rather than the exception in rural areas. My main endeavour has been to show that even with small transformers, of outputs as low as 60 kVA, it is quite reasonable to consider the installation of automatic voltage-regulator equipment. I could easily have taken a larger size of transformer substation of the order of 200 kVA and made it a very easy case with a low unit cost for lighting. Mr. Sumner makes the serious slip of suggesting that the same number of lighting units at a very low load factor might be sold on a 2-part tariff. Obviously, by the time all consumers are on the two-part tariff, the load factor on the transformer must have gone up considerably and a new set of conditions will then apply. I am afraid, therefore, that I must entirely disagree with Mr. Sumner's contention that the case should be based on a profit of £18.

Mr. Sumner agrees with me that a value should be placed on regulation when purchasing distribution transformers, although I cannot agree with his contention that there is any complication in the present-day automatic voltage regulator. There is probably no simpler piece of mechanism, particularly in the case of the moving-coil type.

With regard to the last two points raised, the transformer quoted in the example on page 42 was purchased some few years ago, a short time before the vogue for standardized sizes was really effective. Present-day prices, however, are governed by kVA output without any relation to standard sizes or, even, possibly the transformer cost, so that there would be no material

saving in purchasing a transformer of another size. With reference to the last paragraph on page 33, the normal procedure is to assume that the copper loss of a transformer is proportional to the load, the load itself being a fixed and predetermined figure at any instant. The kVA load, however, is not fixed and predetermined, being itself greater or less as the voltage is greater or less. The only factor which can be said to be fixed is the actual ohmic load of the lamps, radiators, and wireless sets, on the distributors. It would be quite out of the question to argue that, whichever of the two transformers were installed, the transformer with poor regulation would have a specially controlled voltage applied to its high-tension terminals to nullify its bad regulation. It is obvious that in both cases the high-tension voltage applied must be irrespective of the regulation properties of the transformer, and this must be the starting-point of any calculations.

Mr. Fennell has shown the manner in which copper losses can vary between two extreme cases. In practice, however, load-curves day by day and year by year, following as they do the habits of men, all have a predetermined shape and, consequently, the factor N can be calculated accurately for them. Mr. Fennell points out that this factor might very usefully be employed in the calculation of the line losses in the running costs of indirect bulk supplies from the grid system, as detailed in Schedule 3 of the 1926 Act. I have already employed this factor for cases under Section 13 of the Act, and it appears to be quite acceptable to the Central Electricity Board and to the Electricity Commissioners; I suggest that it might usefully be employed almost as a standard method.

Mr. Bolton briefly refers to the psychology of this problem, and it is on this aspect that the difficulty lies in endeavouring to formulate a theory of revenue loss due to regulation. I have purposely avoided cases where extreme regulation occurs, since under such circumstances a consumer might replace his lamps, or fires, or even reject electricity as a service. I have, furthermore, purposely avoided consideration of any apparatus except lamps, fires, and wireless sets, since it is only within this group that there is a reasonable argument for revenue loss. It is undoubtedly a difficult problem, but in view of the alarming loss which is apparent in some instances, there is no question that a big measure of consideration ought to be given to the principles which I have endeavoured to elucidate.

Mr. Norris refers again to an extreme case. It is, of course, hardly ever possible to measure the cost of bad service, but I might suggest an unscientific extrapolation of the results I have put forward in the paper. For comparatively small variations, there appears to be a large loss. Might I not suggest that by proportion, under really bad conditions, the loss must be enormous owing to complete rejection of electricity as a service.

Mr. Norris has stressed another aspect of voltage regulation namely, its relation to the actual cost of the network. In my own experience a similar case occurred in connection with a long low-tension line in a rural area fed from a 50-kVA transformer. Improvement of the voltage at the far end of the line could be accomplished either by installing an additional transformer at the remote end and feeding it from a new 11 000-volt extension at a total cost of £600, or by installing an automatic voltage regulator about one-third of the way along the line and a static balancer towards the end of the line, at a cost of £120 inclusive. The latter method was adopted and an entirely satisfactory arrangement was effected, sufficient, indeed, to take care of conditions for many years ahead.

With reference to page 44, Mr. Norris points out that it would have been better to have installed the transformer with the bad regulation coupled with an automatic voltage regulator. I suggest that probably on-load tap-changing gear would have been cheaper, but in any case the main point is that revenue loss would, with certainty, have been avoided by the method he suggests; it is an extremely interesting point and worthy of much consideration when planning new distribution substations.

I am very much obliged to Mr. Ayres for the consideration he has given to the use of effective network impedance for the calculation of voltage regulation. He points out that the regulation may be due to a variety of causes such as the moving of the centre of gravity of the load, but, whatever the cause, it appears to be a statistically demonstrated fact that with reference to any distributor load the effective network impedance is lowest when the distributor load is at its maximum. This fact should be useful for network calculations generally. It gives me much personal satisfaction to know that, from his great practical experience of the subject, Mr. Ayres agrees generally with the principle of revenue loss. He will of course appreciate that, in attempting to generalize on the subject, there may be points in my paper which do not apply to some of the particular cases he has in mind.

Mr Cowell raises a point with regard to industrial heating, kilns, and annealing furnaces. I have recently dealt with a case of large steel furnaces, with a loading of 4 000 kVA, where under reduced voltage conditions the steel output was badly diminished, resulting in strong complaints from the manufacturers.

Mr. Cowell's suggested method of running is, as an operating condition, probably better than maintaining the voltage continuously at + 4 per cent. As stated on page 38, the maximum revenue is obtained by maintaining the voltage at its maximum all the time. Additional formulæ are given on page 47 for estimating the increase in revenue under other conditions, and the condition which Mr. Cowell suggests lies between giving a constant-voltage supply at declared voltage and at 4 per cent above declared voltage. As he states, the revenue loss will be negligible by operating in the manner he suggests, because the low voltage is only supplied under light-load conditions. Mr. Cowell makes a useful contribution in pointing out that the on-load tap-changing gear would effect further savings in losses.

With regard to Mr. Budgett's remarks, the paper is based only on a.c. distribution and does not apply to direct-current where ampere-hour meters are employed under similar conditions. Mr. Budgett points out the difficulty of installing regulators on long lines. In such a case Mr. Cowell's proposed method of operating will largely assist; that is to say, by compounding the regu-

lator with the load there would be no danger under periods of low load in supplying too high a voltage at the near end of the line.

I think that Mr. Grimmitt has perhaps misread the intention of my remarks in the second paragraph of the Introduction. It was rather my endeavour to point out that the engineer can easily deal with the problem of voltage regulation, but in 9 cases out of 10 the cost of doing so rather debars him, because there is apparently no economic justification for spending the money.

Mr. Grimmitt appreciates the difficulty of the problem, which at one time appeared almost insurmountable to me. The main object has been to prepare a theory to show the revenue loss in a number of particular cases, with a view to indicating that this loss is of such a magnitude that the principle should be undoubtedly considered along with other accepted factors entering into the design of distribution systems.

Messrs. E. B. Wedmore and W. S. Flight (*in reply*): We have endeavoured to introduce some new ideas into discussion of the subject of voltage variation. That we have succeeded, at any rate in shifting attention from the voltage at the consumer's terminals to the voltage at consuming points, is shown by Mr. Nimmo's criticism of the title of our paper, a title which would have been considered appropriate in any previous treatment of the subject. We have also introduced new criteria for determining the quality of supply, which we hope will be useful to supply undertakings but which are, however, difficult to embody in regulations.

Mr. Nimmo asks for some further explanation. We have suggested in effect that if a large undertaker, A, gives a supply which shows an average departure of, say, 2 per cent from declared voltage and a maximum departure in the most difficult areas somewhat exceeding 6 per cent, this will be a better supply than that given by undertaker B who under easier conditions has had no difficulty in working within the maximum limits of $\pm$ 6 per cent, but for lack of attention now shows an average departure of, say, 3 per cent. It is difficult to justify the use of maximum-departure limits as the sole gauge of quality of supply, and if these limits are to be tightened up we suggest in effect that there might be some easement of the conditions for cases of the type indicated in our paper.

We accept Mr. Ayres's comments on the "branching factor." This factor does not readily admit of mathematical treatment, but if it had been omitted from the paper we might have been subject to severe criticism. This somewhat indefinite term is used as a reminder that, as the load increases, this increased load is not all carried throughout on the same conductors but additional conductors are switched-in in parallel, thus reducing the drop to some extent. This would be particularly the case beyond the consumers' terminals.

In referring to the use of series resistance we are introducing no new idea. Such resistances have been used, for example, in the Bankside station of the City of London Electric Light Co. Their use on very short feeders enables the voltage to be raised at the station during heavy-load periods without too high a voltage being given to the consumers fed by these short feeders.

We hope that one result of our work will be that the subject of quality of supply will receive increased attention. We welcome, therefore, the contribution of Mr. Fordham Cooper, and hope that through the technical Press and in other ways supply engineers will continue to exchange ideas and information on this subject.

The statistical study of voltage variation on a given system involves laborious calculations, and the larger undertakings at least would find it profitable to employ instrumental means of reducing the labour. When first considering an instrument of the type mentioned by Mr. Knowles it occurred to us that it might be open to the objection of possible difficulty in securing that the contact-maker would touch only one contact at a time, but Mr. Knowles advised us that this problem had already been solved in another connection.

In conclusion we would mention that the E.R.A. would be glad to hear from members pursuing any aspect of this problem of voltage regulation.

DISCUSSION ON "PRIVATE PLANTS AND PUBLIC SUPPLY TARIFFS"* AND "LOSS OF REVENUE ON HEATING AND LIGHTING LOADS, DUE TO POOR VOLTAGE REGULATION"†

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 6TH APRIL, 1936

Mr. F. H. Clough: It seems to me that the difficulties and their suggested remedies described in Mr. Naylor's paper arise from a too-extended use of the low-voltage distribution mains. He mentions that transformer capital costs are relatively low; it would seem, therefore, that more transformers should be used to feed the distribution mains at more frequent points. These distribution mains would not then be called upon to undertake the duties of transmission as well as distribution; the transmission would be carried out at a suitable higher voltage.

Mr. Naylor mentions a form of transformer with saturated leakage path; such transformers have been made by several manufacturers, but have not been found very satisfactory. They introduce harmonics into the voltage wave, and do not give a boosting effect if the power factor is a little below unity.

Mr. F. J. Elliott: I do not agree with Mr. Sumner's statement (page 312) that "the majority of owners of private plant have no knowledge as to the cost per kilowatt-hour of power production from their plant." My experience leads me to a contrary conclusion. I have found that the manufacturer has not only an intimate knowledge of the costs of private plant, but also an equally detailed knowledge of the tariffs of various supply undertakings.

Mr. Sumner's figure of 0·4d. per unit for the running costs of Diesel plant would appear to be a very fair one. In the latest report of the Diesel Engine Users' Association, figures relating to some 34 stations are given, and it is rather refreshing to find that wide variation in costs of production is not confined to authorized undertakers; the running costs quoted in this report vary from 2·5d. to 0·33d. per unit.

A plant at Chelmsford shows the lowest figure for 12 months, namely 0·33d. per unit, and as the average costs of this particular plant over a period of 13 years amount to 0·39d. per unit the figure quoted would appear to be a reasonably consistent one. This plant was operated at a load factor of 17 per cent, and, adding the author's weighted standing charge of £4·95 per kW, we arrive at a total cost of 1·23d. per unit. A public supply undertaking operating in the Midlands would supply this consumer on a standard tariff at an overall cost of 0·9d. per unit.

The next lowest running cost quoted in the Association's report was obtained by a large heavy-oil engine manufacturer, and showed a figure of 0·39d. per unit with a load factor of 45·5 per cent. Again using the author's figures for standing charges, the total cost in this case will be 0·67d. per unit, and using the same public supply tariff the cost would be 0·48d. per unit.

These facts indicate that with a load factor varying so widely as from 17 to 45 per cent public supply can show lower costs than private plant.

Mr. P. Wardle: In Table 4 of his paper, Mr. Sumner quotes a figure of 270 units as representing the annual consumption of a small farm having a 2-kW plant, and 6 600 units for a large farm having a 30-kW plant. I should be interested to learn what he considers to be the likely annual revenue from an ordinary-size farm, such as we have in Shropshire and Staffordshire, assuming the supply is used for lighting, power, and dairy purposes.

In presenting his paper Mr. Naylor said he was not concerned so much with low voltage as with poor voltage regulation. I presume, however, that he attributes the loss in revenue to low voltage. Seeing that there is such a thing as high voltage, probably due to a badly balanced load, or to being in close proximity to the substation supplying the network, has he taken into consideration the possibility of the high-voltage consumer subsidizing the low-voltage consumer?

Also, can Mr. Naylor give any information as to when it becomes an economical proposition to substitute a voltage regulator, which might be considered to be a temporary expedient, with a substation at a distant point in the network?

Prof. W. Cramp: I doubt very much whether the basis which Mr. Naylor has chosen, namely loss of revenue, really exists. When the voltage falls, as it always does at some of the peak hours, the usual plan is to switch on more lights and more heater units. The consequence is that the local authority tends to gain by a fall in the voltage.

A suggestion has been made, though I have never seen it put into practice, that series condensers should be used to adjust the voltage. With a lagging power factor, a series condenser will give an automatic rise in voltage, and although this plan would be helpless for a large power plant it is quite possible for small loads.

With regard to Mr. Sumner's paper, I think that some of the cases, though interesting, are not typical. For

* Paper by Mr. J. A. Sumner (see vol. 77, p. 310, and vol. 79, p. 61).
† Paper by Mr. F. S. Naylor (see page 33).

example, he has an instance in which a steam supply is required for heating purposes in addition to power. This is an unfortunate case, because the heat is only required during the mid-winter months. It is then difficult to make out a case for a bleeding turbine, as against the supply from the power authority. In the North of England there are chemical works requiring quantities of steam far larger than those required for power purposes. It is then impossible to make out a case for the public supply. Power becomes merely a by-product. The figures given by Mr. Sumner on page 317 are unfavourable to the private power-plant because though steam is not required for heating in the summer, the boilers are still used for the power plant. In Birmingham, at the University, steam is required for heating in the winter only and a reciprocating engine of the bleeding type is then used, the cost of power being small. But a Diesel engine takes the summer load, with the result that the cost of power is much less than in Mr. Sumner's example.

Some of the other figures also should be modified. For instance, in Table 3 figures of 10 per cent depreciation, 5 per cent maintenance, and 5 per cent interest, are given. The total of 20 per cent is much higher than is reasonable, even allowing for obsolescence. The total figure, instead of being 20 per cent, should be about 12 per cent. For distribution (i.e. cables, etc.) the figure can be still lower. The author shows how enormous the capital costs of distribution are, so that, when these percentages are corrected, he will find a better case for the private plant.

The author apologizes for taking load factor as a basis, but I think this basis is the only one possible when comparing a private plant with a public supply. It is my experience that not only where large quantities of steam are required for process work, but also where the load factor is really high, the supply authorities cannot compete with the private plant. I have had many instances where, against my will, I have been forced to put in steam or Diesel engines. A particular case is that of a flour mill which runs, say, 140 hours a week. Such a plant has a steady load, and the whole mechanism must run together at one speed. In this case, even with electricity at ⅜d. per unit or less, it can be shown that the private plant will often be cheaper. Mr. Sumner's paper would have been more complete if it had contained references to loads of this kind.

Again, in a works which must operate as one unit, where there is a steam engine, alternator, and separate exciter, all the induction motors can be permanently connected to the alternator. No motor starters are needed. At starting, the exciter is first run up and the stationary alternator is excited to its full value. Then the alternator is run up gradually and every motor speeds up with the alternator.

There is, however, one factor affecting the operation of a private plant to which the author has not referred, and it cannot be assessed in terms of £ s. d.; it is that "responsibility factor" which is thrown upon the manager of the works by the ownership and running of a power plant. How much of the manager's time is taken up in buying coal, checking purchases, looking after ash-removal, etc., cannot be put down in the accounts, but it is very real; and I believe that in many large works it would pay to cut out the private power plant for the simple reason that by so doing the mind of the manager is relieved of this encumbrance.

I sympathize with Mr. Sumner in his appeal for uniformity of tariffs, except from one point of view. I think that standardization can be overdone. Conformity always kills initiative, and the thing to do is to get the experience of non-conformity until the best plan becomes obvious.

Mr. H. Hooper: The subjects dealt with by Mr. Naylor and Mr. Sumner in their papers are closely related, in that poor regulation means loss of revenue and also dissatisfied consumers, and satisfied consumers are the best advertisement for any supply undertaking.

Dealing with Mr. Sumner's paper, standardization of tariffs is at present a physical and economic impossibility. I give, for example, one concrete case, and there are many other similar ones. A firm wanted to make aluminium. It was estimated that they would have a consumption of 50 million units with a maximum demand of approximately 5 000 kW on peak and 7 500 kW off peak. An inquiry was sent to many supply undertakings in the country asking for a tariff which would be economical taking into account the purpose for which the supply was required. In due course this inquiry reached several supply authorities in the Midlands; it asked for cheap electricity supply on the assumption of labour benefits to the community of the town selected. Some towns wanted the works, and one town considered putting up part of the capital to induce the firm to erect the works in their locality. The tariff which was finally accepted was an economic one, all factors being considered, and the supply authority concerned is well satisfied. Cases could be given where certain big firms with large interests in all parts of the country have coerced one undertaking into giving an uneconomical tariff, and have then proceeded to demand similar tariffs in other districts where there are other works belonging to them, thus creating a vicious circle. Unfortunately, some electric supply authorities make a practice of offering terms of supply for certain power consumers which are decidedly uneconomic. They are, of course, doing it at the expense of better-priced units. Taking all these various aspects into account, and bearing in mind the fact that every electric supply undertaking is responsible for its own balance sheet, it is easy to see that at the moment it is an impossibility to get a standard tariff on the lines of those of the telephone and telegraph systems.

Another point raised by Mr. Sumner is the question of obtaining the consumers' costs. Generally speaking, many private-plant users do not know their true costs, and this is the difficulty which supply authorities have to face when offering tariffs.

There is another factor to be taken into consideration, namely that, generally speaking, the owners of private plant should be prepared to pay at least 10 per cent utility factor value for public supply.

Mr. R. H. Rawll: The determination of the generation costs of selected stations is standardized under a schedule prescribed by the Central Electricity Board; the same methods, if possible, should be utilized in ascertaining

the actual generation costs of private plant. I know of a case in Birmingham where building costs were omitted by the owner of private plant when asked to submit detailed figures of the actual cost of generation. Such items actually cost the consumer money but are often not included, with the result that it appears in certain cases that private plant can generate more cheaply than the supply authority.

Mr. Sumner has been very fortunate in one respect, in that he has been able to experiment in a newly developed area with new tariffs. Most supply authorities in this country are faced with a developed area in which a series of tariffs have grown up. It is interesting to try to ascertain why all these tariffs have come into existence. I think it will be found that in every case a new tariff has been put forward by an undertaking in order to cope with a new type of load, without sufficient thought being given as to the possibility of amending an existing tariff to cover the new business. To simplify existing tariffs is a very complicated matter because we have always to bear in mind, amongst other considerations, those clauses of the Electricity Acts which prohibit discrimination in charges between consumers who receive supplies in similar circumstances. Though I agree wholeheartedly with Mr. Sumner that it is essential we should standardize the basis of tariffs, I hardly agree as to the standardization of charges. If the whole of the supply industry were under a national body, that would be a different matter. As it stands now, with the grid tariffs fixed for 10 years, we have to face the position that each undertaking, with its own distribution costs, has to present an individual balance sheet which is economically sound. Let us standardize the basis of tariffs by all means, but with the present organization of separate distributing authorities, each must naturally determine its own charges.

I am glad that Mr. Sumner has raised the question of selling power at uneconomical rates. I consider that supply undertakings are now taking the wider and national view-point, as distinct from the parochial outlook of a few years ago. Supply engineers are beginning to realize that it is a question of doing not only their own undertaking but also other undertakings throughout the country a very big dis-service by putting forward an uneconomic price for a particular type of load, since all the big industries are aware of the tariffs offered by the various undertakings, large and small.

Another point that Mr. Sumner has raised is the question of the lighting or domestic load subsidizing the power load. It naturally follows that if one is supplying a load at an uneconomical price one must in effect subsidize it from another type of load, otherwise a loss will be made. There must, of course, be a certain degree of latitude in this respect in that one cannot always make every load pay strictly for itself, and there is also bound to be some overlapping, but, nevertheless, definite limits should be observed in such matters.

Mr. J. A. Sumner (*in reply*): Mr. Elliott joins with a number of other speakers at each Centre in disputing the statement which I have made that "the majority of private plant owners have no knowledge as to the cost of power production from their plant," and states that the owner has an intimate knowledge of the cost of private plant. It has not been my experience to find that the latter statement is correct, but I do agree most sympathetically with Mr. Elliott's statement that the manufacturer has an intimate knowledge of the tariffs of various supply undertakings. This knowledge appears to be limited, however, to those which quote lower prices than the manufacturer's undertaking, and we are usually expected to provide supply at a cost which is a little below the cost for the lowest undertaking quoted by the manufacturer. In an earlier discussion it was suggested that I was wrong to suggest that we should obtain for power "what the market would stand," but I am of the opinion that public supply power prices have been forced down in many instances to such low and uneconomic prices as to justify serious steps being taken to form a "ring" which would bring prices back to an economic level. The system of undercutting which now exists with private plant makers and public supply authorities is, in many cases, prejudicial to both interests.

The following Table gives a list of consumptions of certain typical farms in the area of supply indicated the paper, in answer to Mr. Wardle's inquiry.

Transformer capacity installed	Annual consumption	Annual load factor	Cost per unit
kVA	kWh	per cent	d.
2	591	3·5	6·7
2	551	3·0	7·0
5	3 342	7·6	3·6
5	3 040	7·0	3·8

In reply to Prof. Cramp, it would be interesting to have the actual cost of providing supply at Birmingham University because the annual load factor on the Diesel engine must be very low if it is only used in the summer, and the lack of balance between the power and heating requirements must approximate to the case quoted in the paper for the power-heating supply. I should agree, of course, that some of the cases given in the paper are not typical and that it is not possible to make a complete generalization. I cannot agree that 12 per cent is sufficient to cover maintenance, depreciation, and interest, on Diesel plant, although it may be sufficient for steam plant if the possibility of obsolescence is ignored. As regards the special cases of power requirements which are quoted by Prof. Cramp, I am of the opinion that an exhaustive examination of all the factors would show that the public supply can nearly always compete, having in mind the high annual load factors which occur in most of these special cases.

Both Mr. Hooper and Mr. Rawll appear to consider that standardization of tariffs is desirable but impossible. I do not think that it can be achieved voluntarily, for the very reasons of which Mr. Hooper gives instances. But the coercion of undertakings to which he refers seems to compel some authoritative action to be taken, probably on the lines indicated in the latter portion of my reply to Mr. Elliott. As Mr. Rawll observes, if uneconomic prices are quoted for power supplies the domestic consumer must bear the loss and thereby subsidize the power consumer. In this manner the whole of the supply industry is prejudiced.

Mr. F. S. Naylor (*in reply*): There is no doubt, as Mr. Clough suggests, that the present-day tendency is in the direction of greater use of high-voltage supplies with more frequent transformer connections. In fact, when domestic electrification starts to approach saturation—represented by, for example, 10 kW maximum

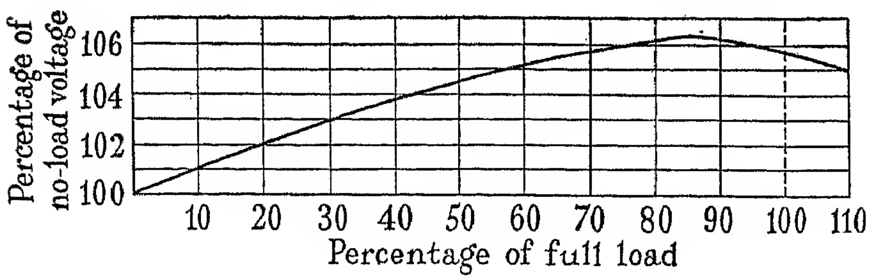

Fig. A.—Load regulation, at unity power factor, of self-compounded distribution transformer.

demand per house—low-voltage distribution must eventually disappear. Until that time, however, the problem of voltage regulation on distributors will be with us. I am very interested in Mr. Clough's remarks with regard to self-compounded transformers. I have had no experience of this type of unit, but the presence of harmonics in the voltage would certainly be unsatisfactory, because it would give rise to noisy substations. I should imagine, however, that this difficulty could be got over by proper design, since this class of transformer has hitherto had little development.

I agree with Mr. Clough that the self-compounding transformer is useless on lagging loads; Figs. A and B show the performance of a particular design. On distributor loads operating at approximately unity power factor this unit should have a considerable field of use. For mixed loads below 0·9 power factor the capacitance

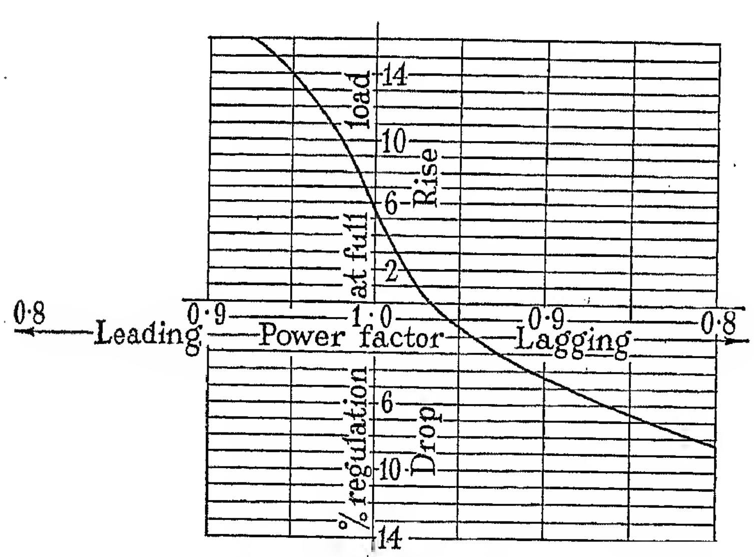

Fig. B.—Load regulation, at full load and with various power factors, of self-compounded distribution transformer.

booster (referred to in my reply to Prof. Cramp) would get over Mr. Clough's objections.

Replying to Mr. Wardle, possibly in my opening remarks I made rather a fine distinction between low voltage and poor voltage regulation. On the other hand, it is important to draw a distinction between the two. Low voltage arising from a too-low setting of the tapping switch can easily be corrected. For example, between no load and full load at the supply end of a distributor the variation may be from declared voltage to declared voltage minus 8 per cent; this can be corrected to a variation of 4 per cent above and below the declared voltage. Whilst low voltage to a certain extent has been corrected by this procedure, the total regulation is unaffected. It is assumed in the paper that in all cases a distribution transformer would have its tappings set correctly, so that with no load on the transformer the maximum permissible voltage would be obtained, namely 4 per cent above declared voltage.

I had not considered the possibility of the higher-voltage consumer subsidizing the lower-voltage consumer. I take it that Mr. Wardle is here suggesting a higher tariff for the consumers supplied with the more constant voltage and a lower tariff for the consumers supplied with a voltage having a poor regulation; this would be a rather complicated matter, and I do not think it would be possible to do anything on these lines.

It is difficult to state generally when it is more economical to install a voltage regulator than to put in a substation. Using automatic voltage regulators

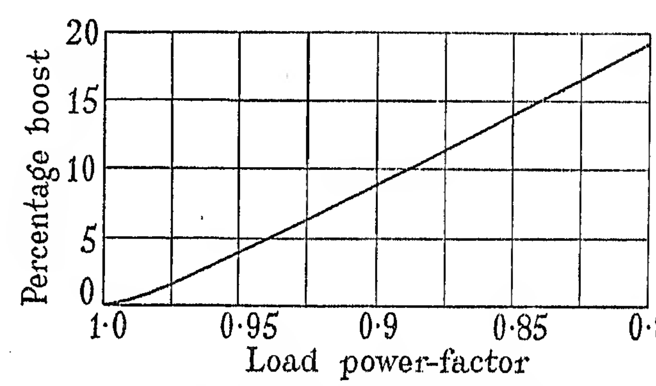

Fig. C.—Maximum boost obtainable, at various load power-factors, with capacitance booster.

would enable a distributor or substation to give a satisfactory supply up to the heating capacity of the cables; beyond this point, additional substations or additional cables would have to be put into use. Mr. Norris in the discussion before the Transmission Section,* and my reply to his remarks, give two examples which illustrate the point Mr. Wardle raises.

Prof. Cramp probably bases his remarks on his own particular experience, but it should be borne in mind that the average house has no more than one light per room and, therefore, the usual thing is for a consumer to put up with poor light during the relatively short period in which the voltage is down, probably being hardly aware of the fact.

I am afraid that Prof. Cramp's suggestion of a series condenser to adjust the voltage would not be satisfactory, on account of the cost of providing a condenser unit which would take the whole of the distributor load. A modification of this, namely the capacitance booster, would, however, be a practicable proposition; the latter comprises a transformer whose primary takes the distributor load and whose secondary has a condenser placed across it.

Fig. C shows the maximum boost obtainable with this device at various load power-factors. It will be observed that at loads approaching unity power factor, which are

* See page 50.

normal for distributors giving supplies to domestic consumers, there is little or no boost. Under normal conditions a simple series condenser and a capacitance booster behave in precisely the same manner and produce similar results, but the booster possesses material advantages. As regards the series condenser, the voltage and the condenser current are fixed by the external conditions, whereas with the capacitance booster these can be selected at will. The size of the condenser can therefore be reduced materially. Consider, for example, a 230-volt single-phase distributor, the regulation at the full load of 25 kVA at 0·8 power factor being 8 per cent at the supply end. The drop across a series condenser would be approximately 35 volts, and the series capacitance required would be 10 000 μF. With the capacitance booster, however, the voltage across the condenser can be selected as 600 volts, the standard value for this class of apparatus, and as a result of reducing the condenser current in the ratio 35/600 the capacitance of the condenser can be reduced to 33·7 μF, which means a considerably lower total cost.

Another danger arising from a series condenser would be that the impedance of the distributor would be thereby reduced, rendering the short-circuit conditions much more severe on any part of the distributor. With the capacitance booster, however, owing to the magnetic characteristics of the transformer, which rapidly reaches saturation, this reduction in impedance—as far as it affects fault conditions—does not take place.

DISCUSSION ON "PRIVATE PLANTS AND PUBLIC SUPPLY TARIFFS"*

WESTERN CENTRE, AT BRISTOL, 11TH NOVEMBER, 1935

Mr. L. Burdes: The data given by the author for private plants are very fair and representative, and will be acceptable to most engineers as a basis for fixing suitable tariffs. The fixed and running charges having been determined for the various classes of prime movers and for different sizes within each class, it remains to design a tariff to take care of these differences.

I agree with the author that few consumers of the type dealt with in the paper have exact knowledge of either their load factor or their power output, but larger consumers often keep accurate records. The user is often confused by standing and running charges, and is usually most concerned with the total annual cost which he has to meet.

The author has presented the worst possible case for electricity because, as he points out, his comparison is a financial one and takes no account of amenity value, which may be of even more importance in some cases. It may, in fact, be sufficiently important to outweigh any adverse financial balance, and doubtless the author has had experience of cases where electricity costs are hardly mentioned during negotiations.

In conclusion, I should like to correct a statement made by the author in his reply to the London discussion (vol. 77, p. 351), to the effect that Section 13 of the 1926 Act prevents prices in urban areas from being increased to enable those in rural areas to be reduced. In actual fact, Section 13 places a limitation on the price to be charged to owners of selected stations. No doubt the author has another Section of the Act in mind.

Mr. W. C. Bowler: I should like to refer to the great difficulty in a rural district of getting down to a price which is acceptable to the consumer. The difficulty lies in the fact that many rural supplies have a maximum demand such as would not permit of their taking a supply direct from the Central Electricity Board, and therefore they are in the hands of the bulk supplier. The maximum-demand and unit charges offered to the undertaking by the bulk supplier are such that it is impossible to get down to a figure which is reasonable and which one could offer to a prospective large consumer.

I would instance a case in the district with which I am associated where the supply undertaking had secured about one-third of the total horsepower available and there was a possibility of obtaining the other two-thirds, subject to the price being reasonable. In the case of two large manufacturers, however, it was impossible to get down to a reasonable figure because of the high bulk-supply charges.

I suggest that some method should be evolved whereby the charges could be reduced so as to enable rural undertakings to obtain these prospective loads. It is not practicable to ask an undertaking, whether company or municipal, to finance out of their rates the difference which would enable them to obtain these power consumers. I can recall one case where it would have cost my undertaking £300 per annum to have got down to a figure which would have obtained the load.

Mr. G. T. Champion: Referring to the use of heat in the steam exhausted from the prime mover, the author states that there must be a continuous use of this rejected heat, whereas the average works only require heating for approximately one-third of the year. These statements are misleading, because the exhaust steam from a back-pressure engine can be used in a continuous manner during the winter months, for factory heating, and can also be used intermittently or otherwise throughout the year to meet process requirements. By efficient control it is possible to effect a satisfactory heat-load

* Paper by Mr. J. A. Sumner (see vol. 77, p. 310, and vol. 79, p. 57).

balance throughout the year, irrespective of whether factory heating is required. A typical case is in connection with the storage of hot water by directly exhausting through suitable nozzles into cold-water storage tanks; sufficient heat energy having been stored in the form of hot water, the back-pressure set may be closed down and the load for the time being taken over by some other form of economical unit, such as a crude-oil engine. I cannot agree that it is necessary to run the back-pressure plant continuously, as stated by the author.

Moreover, I cannot agree that the most efficient use occurs where a pass-out turbine is used; this, in my opinion, entirely depends upon circumstances. One advantage of the pass-out turbine is undoubtedly due to the fact that steam may be passed out in a superheated condition, which at times is necessary to meet process requirements; the same advantage cannot of course be claimed for the back-pressure reciprocating engine. I regret that the author does not make reference to the steam accumulator, working in conjunction with back-pressure-engine plant, as this would have had a decided bearing on his general remarks.

Respecting the use of crude-oil engines, no form of heat engine yet made to run on commercial lines will compare as regards economy of working with a back-pressure-engine installation working under correct heat-load-balance conditions. Apart from this, the crude-oil engine will continue to hold its own as a prime mover, load-factor conditions being one, if not the most important, item for consideration in this connection. I agree that the crude-oil engine is an extremely useful adjunct to the back-pressure or pass-out engine plant, for dealing with peak loads. For some time past, exhaust steam from back-pressure and pass-out prime movers has not only been giving service for process work and mill heating but has also provided electrical and heating service in connection with housing schemes run on composite lines.

Mr. H. G. Weaver: I should like to make a few remarks from the point of view of the large power consumer. In my view, the 30-minute period on which the average maximum demand is based does not in all cases give a correct indication of the size of generating plant required to supply the load. The British Standard Specification for generating plant calls for an overload capacity of 25 per cent for 2 hours, and I suggest that the average maximum demand should be based on this period. As an example, take the case of a steel rolling-mill the normal average maximum demand of which is 4 000 kW. Owing to some trouble with the heating furnace there may be a drop in the temperature of the steel for half an hour, and, owing to the well-known fact that the power required for rolling increases rapidly with a decrease in temperature, the load may increase to 5 000 kW during this period. This extra load would be carried without trouble by a private plant, at the cost of a ton or two of coal. On the other hand, under a two-part tariff, the cost may be hundreds or even thousands of pounds.

With large private plants the standing charges are definitely known, and the cost per unit can be accurately ascertained beforehand for any number of units per annum. The uncertainty as to what the actual cost is going to be is one of the chief objections to two-part tariffs put forward by large consumers.

The author himself appears to be of the opinion that flat-rate charging may return. A graduated flat-rate system following roughly the curve given by private-plant costs is much more attractive than a two-part tariff to potential large consumers, for the reasons already mentioned.

Another point for consideration is the reliability of public supply. Unfortunately the experience has been that, since supply systems were linked up to the grid, public supply has not been as reliable as before. I use the word "reliability" here to refer not only to failure of supply, but also to disturbances such as a sudden momentary drop in voltage of considerable magnitude. With rotary convertors supplying large shunt-wound motors, or with a large battery floating on the busbars, the effect of these severe disturbances is to produce reverse current and open the d.c. circuit breakers, causing a shutdown of the driven plant. I agree with Mr. Hatch's remarks, in the discussion at Liverpool, to the effect that the large financial losses caused by interruptions of process work due to these shutdowns can be of more importance than a small difference in the cost per unit.

Mr. S. Hartland: I wish to draw attention to the author's statement that "In the first place the generally accepted opinion that rural distribution is more expensive than urban distribution, appears to be fallacious." Accepting, for the moment, "the almost constant cost per dwelling on the route of mains," do the mains of the rural areas considered in the paper provide for development to the same extent as those in the urban areas considered? If not, the figures will be misleading. It is a comparatively simple matter (financially) to provide underground mains adequate for load saturation in urban areas, but it is not so simple in rural areas. It is not sufficient to give the capital cost per dwelling; this is but one side of the picture, and to complete it we require the potential revenue per dwelling. To illustrate my point: the large store in the large borough will probably consume as much energy per annum as a village of 50 premises. There are no such stores in the rural areas. I would also refer to Fig. 1, where it is shown that the capital expenditure per dwelling is about the same in both types of areas, up to 60 per cent saturation in rural areas but approximately up to 80 per cent saturation in urban areas. The urban areas, therefore, are able to deal with 30 per cent more dwellings than the rural areas without any corresponding increase in cost per dwelling. We cannot possibly stop at 60 per cent saturation in rural areas; our consumers will not let us.

With regard to tariffs, the future tariff, in my opinion, will not be a maximum-demand charge plus a unit charge, except in the case of large power consumers where it is possible to relate the demand accurately to the demand made on the undertaking: in the case of domestic premises we shall ultimately supply electricity "on tap" and make a fixed charge per annum.

Mr. W. A. H. Parker: Whilst it is true that a large number of private-plant owners spend little time in ascertaining the cost per kWh generated, from my own experience I think the author's statement that the

majority have no knowledge on this point is too sweeping. I find that they invariably keep a close record of the annual running charges, but the fixed charges, such as interest and depreciation, rarely come into the cost sheet as charges per kWh.

When we are endeavouring to persuade owners of plant to take a public supply it is very important that we should, in each individual case, make a full investigation of (*a*) the load factor of the proposed supply, (*b*) the capital expenditure involved in the change-over, and (*c*) the benefits which may be obtained from a reorganization of the productive machinery and the greater facilities for working overtime. We are then in a position to present the full facts to the prospective client, who will generally be impressed with the way the problem has been dealt with.

I purposely stress the importance of making a full investigation in each individual case because there is a tendency amongst some engineers to put forward a figure which has been obtained by averaging the results of a number of investigations, and in this connection I should like to draw attention to Table 2, according to which the average cost per kW of plant installed [item (9)] varies between £1 1s. and £4 3s. for two plants which have practically the same annual output and capacity. The author also attempts to generalize regarding the cost of running Diesel plant, but few will agree with his classifications or costs, especially as the costs per kW installed appear to be based on the averaged costs of 12 large and 6 small plants in one part of the country. Nor will many engineers agree with his statement that the most efficient use of steam is made with the pass-out turbine; the back-pressure engine is more efficient, and when properly applied will produce electricity at a price which makes it difficult for a public supply to compete.

Dealing now with Part 2 of the paper, the initial disregard of the power load is difficult to understand because a good power load generally provides a higher return per £ of capital expenditure, a very important factor when one is developing a rural area with a relatively small domestic load.

The author appears to be in some doubt as to whether electricity should be sold at its actual cost or at a price which is competitive with alternative forms of energy. Salesmanship will show the user that some of the benefits which he obtains from the use of a public supply cannot be assessed in actual money values and that these benefits cannot be obtained with any other form of power. I cannot follow the author's arguments relating to a flat-rate charge of 1d. per unit for both power and domestic consumers. Does he suggest that the large manufacturer, who is at present paying, say, 0·5d. per unit, should be charged more to subsidize the domestic consumer?

Mr. J. A. Sumner (*in reply*): I am very much obliged to Mr. Burdes for supporting a number of the statements made in the paper, because of the practical knowledge which appears to underlie this support. I fully agree that there are many cases in which the "amenity value," or the "invisible exports" relating to public supply, may outweigh the financial considerations. My reference in an earlier discussion to Section 13 of the 1926 Act is quite correct. The effect of Section 13 is to enable owners of selected stations in urban areas to obtain supply from the Central Electricity Board at "selected station price." In this way the Board are precluded from recouping from the urban undertakings any losses which they may incur in providing supply to rural undertakings.

Mr. Bowler points out that there are many small rural undertakings which are having to pay very high prices for their supplies received in bulk because they have not a sufficient demand to permit of their taking supplies direct from the Central Electricity Board, and, I might add, because many of these undertakings are under long-term agreements which were in force before the 1926 Act came into being and which have not yet expired. I fully agree that many of these prices are such that it is impossible to permit of small rural undertakings providing supplies to consumers at prices which permit of proper development. Here, again, is an instance of the chaotic state of prices charged for electricity and of the difficulties which have arisen due to the uncoordinated and piecemeal developments of supply undertakings.

Mr. Champion refers to the case, which I have quoted in the paper, for private plant which utilizes for purposes other than power production the steam exhausted from the prime mover. I quite agree with Mr. Champion that there are many cases where a continuous use of the exhaust steam of a back-pressure engine becomes possible, and we usually hear in some detail about these cases. The purposes of my inserting the example of the back-pressure steam engine was to indicate that there are many cases in existence where the continuous use of this exhaust steam is not possible, also to show that it is not possible to generalize when referring to these cases, as some of the speakers in the discussion appear to have done. I think the whole case for back-pressure steam plant is summed up in Mr. Champion's own words where he says that "no form of heat engine yet made to run on commercial lines will compare as regards economy of working with a back-pressure-engine installation *working under correct heat-load-balance conditions*."

The words in italics really cover the general case for economy of working of any heat engine, but I have attempted to point out in the paper, and it was the main purpose of the insertion of the case of the back-pressure engine, that unless these correct heat-load-balance conditions are obtained, the public supply may be very much cheaper even at £4 10s. per kVA plus ½d. per unit.

Mr. Weaver raises a very large question when he suggests that the 30-minute period is not a correct one on which to base an average maximum demand. I agree that this statement may be correct, but the period is one which is generally imposed by supply undertakings.

I think Mr. Weaver is really tilting at the inherent basis of a two-part tariff, and here again we reach the question as to what is the proper basis upon which to charge for electricity. No two cases of demand are exactly the same, and, as I have maintained in the paper, however scientific we may be in devising our tariffs, it will never be possible to devise a *scientific* basis which could be generally applied. I am strongly of the opinion that in devising methods for charging for tariffs we are relying too much upon tradition (which we are apt to call "science") and too little upon the real modern condi-

tions of costs. For example, a domestic consumer is charged primarily upon a basis of his peak-load kilowatt demand on the undertaking, even though the tariff may not apply directly; yet, for the small consumer particularly, his actual kilowatt demand cost may be almost the smallest proportion of the cost to the undertaking and is difficult to ascertain because of diversity between the consumers themselves and of diversity between the various types of load. I suggest that a load-factor basis of charging for electricity has become obsolete for the small consumer and is rapidly becoming obsolete for the larger consumer, owing to the increased cost of all distribution system standing charges. Even if I were to agree with Mr. Weaver's contention that large financial losses may be caused to a consumer by interruption of process work due to fluctuations or any shut-downs of the public supply, I should have to ask that there should be set against this financial loss the almost certain financial gain, direct and indirect, that has been caused by changing over from private plant to the public supply.

Mr. Hartland's point regarding the relative capacity of the mains in rural and urban areas is a very interesting one. If we can accept that " the cost per dwelling on route of mains " may be the same in rural as in urban areas, then quite obviously the question arises as to whether the mains in each case are of the same capacity.

I would put forward for consideration that if we are only considering the obtaining of sufficient revenue from each consumer to make the distribution system pay for itself, then it does not matter if the rural mains were of less capacity than the urban mains. I am implying here that, for any distribution system, each consumer will use a small amount of electricity for essential purposes and will be willing to pay a fairly high price for it. This principle is supported by a good many small undertakings who still assume that there is no point in providing large mains because they can install smaller mains with less capital expenditure and then sell a small amount of electricity at a high price. But consider the question from the point of view of progressive electricity development. If the rural mains were of less capacity than the urban mains, even though the " capital cost of dwelling " were the same, the rural system must obviously be less efficient.

I agree very fully with Mr. Hartland that the method of charging in the future for domestic premises will be and should be on a basis of supplying electricity " on tap " with a fixed charge per annum and without any unit charge.

I would assure Mr. Parker that in the undertaking with which I am connected, in every case where a public supply has been proposed an investigation has been made by the supply authority and a report placed before the prospective consumer showing on one side the costs of running his private plant, and on the other side the annual maximum demand and annual consumption which I have estimated, also the estimated cost of taking the supply from the public mains.

SCOTTISH CENTRE, AT GLASGOW, 14TH JANUARY, 1936

Mr. J. B. Mavor: One type of private plant which the author has not dealt with is that where a prime mover or driving engine is required; for example, the case of a compressor or of a mill that may have process work to do. In this field the Diesel engine will, I think, challenge the public supply at its best.

Mr. H. M. Stronach: The paper apparently deals solely with conditions met with in rural supply areas. The cost of private industrial plant operation shown in Table 2, giving a total cost per unit of well over 1d., does not obtain in the city of Glasgow.

The load factors mentioned in the paper vary from 54 to 11 per cent; industrial works in this city have usually load factors of about 26 to 16 per cent, and a total cost per unit of over 1d. for public supply would be hopeless; the public-supply tariff is more of the order of $\frac{1}{2}$d. to $\frac{3}{4}$d. per unit, and private plants with costs such as those indicated by the author offer no competition. In my opinion private industrial plants in a dense city area cannot hold a candle to public supply unless there is some other factor present such as the production of heat or steam for process work, and the electrical energy required is a by-product.

The costs given in Table 4 for domestic supplies from private plants are interesting, but are never met with in city areas.

The author remarks that private-plant owners generally know all the details regarding the power required and its cost; but my experience is that they know very little other than that it costs them, say, £500 per annum at present. One has to work out their probable maximum demand and annual consumption, and convince them that under public supply the cost will be less.

Mr. A. K. Roxburgh: I do not propose to make any comment regarding the comparison between private-plant supply and public supply, because I agree with Mr. Stronach's suggestion that with very large undertakings the rates are so low that for anything but a large private plant there is no question of competition. I would, however, emphasize the point that the figures of cost put forward by the owner of a private plant when meeting the supply authority's representative often do not take into consideration all the costs.

I am interested in the author's statement that rural supplies should be given as cheaply as urban supplies. Perhaps it may apply to districts such as exist in the Midlands and the South of England, where the population is very much more dense than it is here; but it is not a condition which we would expect to find in Scotland. One has only to travel over the countless miles of roads in Scotland, in our own areas close to the city, to find that for miles there is not a single dwelling, or at any rate only a few isolated places of the " but and ben " type. This prompts one to ask " Is it an economic proposition to attempt to supply the rural consumer at the same rate as the city dweller? " With regard to the supply of electricity to rural areas, I think we are wrong in estimating the value of the supply in terms of kilowatts or units. The average rural consumer does not know anything about kilowatts. He is not really concerned with the number of units; what he

is concerned with is the service which the presence of an electricity supply can give him.

On page 312 the author states that it is probable that the difference between rural and urban undertakings is to be found in the relatively heavier and temporarily unremunerative expenditure which a rural undertaking must incur in the initial stages, with the possible consequence of a greater accumulated deficit before financial equilibrium is obtained. One is justified, in dealing with a rural supply, in making some slight additional charge, such as calling for a guarantee or a certain minimum annual payment per consumer, to assist over the period of development. Under this system both the supply authority and the consumer contribute towards the pioneer work, and after all, as we hope that each will benefit, each party to the arrangement should bear a fair share of the cost. We find that the farmers in Scotland generally are backward in taking advantage of the public supply, and in my opinion they are not yet what one might call "electrically conscious." We read in Table 4 that the annual load factor of a small farm is 1·5 per cent. This does not suggest a very profitable type of consumer.

On page 323 the author advocates 3-phase lines rather than, as have been adopted in some districts, single-phase extensions. I agree with him; when it is decided to run an extension line it is generally assumed that some power load will be acquired in the future, and, usually, it is not very long until a demand for power is made. We find that the limiting size of the line for Scottish rural work is 0·04 sq. in. or its equivalent; owing to the very difficult contours in some parts of the country, a more expensive line would be the result of using a conductor of smaller size.

Mr. N. C. Bridge: There is one question I should like to put. This is in regard to Table 1, where it is claimed that the capital expenditure per dwelling is more or less the same for rural areas as for urban areas. Many of us must be surprised at any such statement, and I question whether it can hold, assuming the same reliability factor for the two supplies. It occurs to me that this factor has a very big influence on the capital expenditure per dwelling, and I cannot imagine that the consumer will get the same degree of reliability, or continuity of supply, in the rural area as in the urban area without a much heavier expenditure. I have in mind here not only the question of overhead lines as against underground cables, but also the feeding from both sides to any given point of supply, and the possible remoteness in the rural area of the mains engineers in charge when an interruption occurs.

Mr. Alexander Campbell: On page 312 the author remarks: "It is probably correct to say that the majority of owners of private plant have no knowledge as to the cost per kilowatt-hour of power production from their plant." I do not think this is a correct account of the present position, because owing to the keen competition in industry most employers are nowadays very keen to cut down costs. The private plant owner has therefore to consider whether his plant is going to pay him better than the public supply will.

Turning to Table 2, I think it is a pity that the author does not give some examples from the textile industry. The private-plant owner, if he is buying his coal at a cheaper rate than a supply undertaking, is bound to be able to generate his electricity at a lower cost than the latter, even allowing for interest and depreciation on his plant.

Mr. G. Austin (*communicated*): I have always been of opinion that the maximum-demand system is wrong, and I think that this system has done much to hinder the adoption and expansion of the use of electricity. It is a one-sided scheme, ignoring as it does the vital interests of the consumer, and, pressed on him as it has been, it irritates and antagonizes him beyond measure. A few examples will serve to illustrate my point:—

(1) An engineering works has a fairly steady load, but in the nature of things peak demands are unavoidable, and, despite the best endeavours of the management, the maximum demand may suddenly increase one day and spoil the whole calculation for the quarter. There is something wrong when a consumer has to be worried and handicapped in this way.

(2) In many works, extra power demands are necessary from time to time for testing, and it becomes prohibitive to assess this extra power on a maximum-demand basis. Consequently, the principle breaks down and has to be departed from.

(3) In such cases the consumer will often be in a better position if he provides separate generating plant for test-load purposes, rather than pay on a maximum-demand basis. The figure of £2 10s. per kW per quarter, which is a usual one in this district, works out in most cases at £10 per kW per annum, and this, for test-load demands, would soon amount to a prohibitive sum. The consumer could probably buy independent test plant with the excess he would pay on maximum demand during, say, 2 years. He would then have something tangible for his money, and avoid the maximum-demand charges of after years. Here, again, the maximum-demand principle breaks down. (Power supply authorities are, of course, alive to this aspect of the problem and usually compromise with the consumer on the basis of a limiting rate per kWh consumed.)

(4) Suppose a consumer paying on a maximum-demand basis to be desirous of installing electric heaters in the office and officials' quarters throughout the works; the first thing he is faced with is a maximum-demand charge of £20 per annum for each 2-kW radiator —before even a single unit is consumed. The proposal is therefore turned down. Clearly, the maximum-demand principle also fails to meet this case.

(5) If a compromise has been made on the basis of a limiting rate per unit consumed it will probably be found that the works are paying about double what the owners, and even the employees, pay for heating and cooking in their own homes. This suggests that there must be something wrong with the maximum-demand principle.

(6) The works with the highest load factor on a public supply in Britain is said to be that of a large cement manufacturing company. In that factory there are two electric navvies driven by constant-current machinery which has the property of converting overloads on the motors into reduced demands on the supply system.

These machines are to some extent instrumental in helping to attain the high load factor, and at the same time their advent has enabled the output of the factory to be increased by some 20 per cent. The second means of attaining the high load factor is a system of alarm bells, giving warning whenever the maximum demand is being approached. Immediately the alarm bells ring, the operators reduce the machine speeds so as to keep the demand within a predetermined figure. A cheap rate per kWh is obtained at the expense of reduced output of the factory. The system has operated in this case to sell the product at a price rather lower than the power company had reckoned on, but at the expense of the consumer curtailing his demand. The maximum-demand principle again fails; it suits neither the supplier nor the supplied.

Mr. A. R. Beattie (*communicated*): I agree with the author that the majority of private-plant owners may not know their costs per unit; but surely this majority is made up of the owners of the very small plants and not of owners of plants of, say, 500 kW and upwards, or, indeed, of industrial plants where the cost of power forms a fair percentage of the total production costs.

The part of the paper that interests me most is the section headed "Steam Plant for Combined Power and Heating" (page 316). The author mentions works-heating as a typical process steam load, and that only in exceptional cases can rejected heat be used for more than one-third of the year. This to me is rather an unfortunate statement; I do not consider the author has done justice to the textile and paper-making industries, to mention only two, where continuous use of rejected heat is practically universal. The case quoted, in which the boiler efficiency is only 55 per cent and the running time for process heat 35 per cent, could hardly have been better chosen had proof of inefficiency been the sole object of the test. In view of the low thermal efficiency of such a plant it would be easy for a public supply undertaking to vindicate its claims. Fortunately there is another side to the picture, as I have found from my own experience of an industrial concern in India.

For instance, in one combined power and heating plant with which I have been concerned, the yearly average boiler efficiency is 72–75 per cent, and the average overall thermal efficiency of the plant for the same period is 53 per cent, with an all-in-cost per unit generated of 0·170 anna (0·191d.). Now making all due allowances for cheaper coal and other charges in the instance mentioned, I would suggest that the case for combined power and heating systems can be easily proved; and that fallacy of costs, often hinted at in connection with such plants, does not usually exist.

Mr. J. A. Sumner (*in reply*): Mr. Stronach is one of the few speakers who agree with me that private-plant owners do not usually know the detailed cost of their private supply. Most speakers do not appreciate that I was referring chiefly to a knowledge of the division of costs between fixed and running charges.

As Mr. Stronach and Mr. Campbell state, many owners know their *total* annual costs of supply with reasonable correctness, but their costs are not kept in such a manner as to permit them to make a comparison with public supply charges, which are usually made on a two-part basis requiring a knowledge of demand and consumption. It has been asked in the discussion why they should be required to know these divided costs, but it is obviously essential to know them before criticizing or contemplating taking a public supply.

I have much sympathy with Mr. Austin when he illustrates the disadvantages which a consumer incurs who is paying on a basis of maximum demand. The diversity between power consumers is fairly good, and if a power consumer is paying £10 per year per kW of maximum demand, as quoted by Mr. Austin, some concession should be made on account of diversity. Unfortunately, there are more cases where the power consumer is paying much less than one-third of this figure and the income from power supplies is too low to permit of any concessions being made for special cases.

Mr. Beattie, in common with many other speakers, refers to the special case of power requirements in the textile and paper-making industries. These special cases are, of course, outside the scope of the paper, but it would be very useful and interesting if the costs could be obtained for a large number of these cases and the results classified and published.

In reply to Mr. Roxburgh, I think that it is true that rural undertakings are usually a modern development and, for that reason, have not yet been fully developed. They are in the position that most urban undertakings were, say, 30 years ago, and I imagine that in those days even urban development was not looked upon as an unduly remunerative investment. Similarly, the rural undertakings have not had the supply available to rural consumers for a sufficient length of time to make them, as Mr. Roxburgh remarks, "electrically conscious"; many of them do not therefore produce an annual revenue which is sufficient to pay even the annual fixed charges involved in providing the means of supply. As the age of the rural undertakings increases so, I suggest, will they become more remunerative.

THE MEASUREMENT OF DISCHARGES IN DIELECTRICS

By A. N. ARMAN, B.Sc., and A. T. STARR, Ph.D., M.A., Associate Members.

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SUMMARY

The importance is emphasized of being able to differentiate between an increase in the power factor of a dielectric due to gaseous ionization and an increase due to other causes. The necessity of being able to detect discharges before they have caused sufficient damage to give rise to a change in power factor is also pointed out.

A description is given of various methods of discharge detection which have been investigated, together with some details of the apparatus finally adopted and used.

Methods for eliminating from the measurement all discharges external to the test sample are dealt with in some detail, this being an essential feature of apparatus for use on high-voltage testing circuits.

The last section of the paper describes some of the practical uses of the apparatus.

In the Appendices the various circuit arrangements are examined mathematically, and expressions are evolved for each method which provide the means of converting the readings obtained into the actual high-frequency current flowing in the dielectric.

INTRODUCTION

The term "ionization" is used in cable engineering in two different ways; (*a*) to represent the formation of free ions in a gaseous space, and (*b*) to represent a variation of power factor (p.f.) with voltage. It is regrettable that the term is used for the latter phenomenon, for this is likely to make us assume that when free ions are produced in gas spaces the p.f. varies, and when the p.f. varies then free ions are being produced It is fairly certain that the former statement is true, but not the latter. In order that there may be no confusion, we will reserve the term "ionization" to represent the formation of free ions by collision, and speak of variation of p.f. as "p.f. variation." It has become a custom with cable engineers to measure the p.f. at different voltages and temperatures, and to attempt to ascertain the behaviour of the dielectric by these measurements. It is clear, however, that measurement of the p.f. alone cannot tell us all we want to know. For example, if the p.f. increases as the voltage increases, we cannot be certain whether the increase of p.f. is due to ionization in the gaseous spaces or to an increase in p.f. of the dielectric material itself.

There are three main types of cable breakdown.* Firstly, there is breakdown by disruption or puncture, which occurs immediately if the voltage is greater than a certain fairly definite value. This type is not usually met in cables, unless a large surge occurs. Secondly, there is breakdown by thermal instability; this occurs when the rate of increase with temperature of the heat produced by dielectric losses is greater than that of the heat conducted away at the position of equilibrium. Thirdly, there is breakdown due to a slowly progressive treeing and coreing in the dielectric, caused by ionization by collision, leading eventually to thermal instability at the thermal centre of the coreing.

The second type is occasionally met and is fairly quick; i.e. the time from the beginning of instability to breakdown is not very long, although the instability may not commence in the cable for a long time. The third type is probably the most frequent and takes a long time to develop.

The measurement of p.f. is of prime importance in seeing whether thermal instability is being approached, as the heat produced by the dielectric losses is proportional to the p.f.: but it is not at all probable that the p.f. gives much indication as to whether ionization is taking place, especially when the treeing and coreing are in the early stages and the bulk of the dielectric is sound.

This paper is concerned with a method of measuring this ionization directly, and not by its effect on the 50-cycle p.f. If we use the method in conjunction with the Schering bridge we can see whether, in any particular case, a variation of p.f. is due to ionization or to other causes; also, we can determine whether a given dielectric is undergoing local ionization long before the extensive treeing and coreing occur that are required for an appreciable change in the p.f.

METHODS OF DETECTING IONIZATION

There have been a number of attempts in the past to detect ionization. If the ionization is very violent, it makes a noise which may be heard. If there is a local spot of strong ionization, the fault can sometimes be located by means of a telephone diaphragm and a stick. The stick is fastened at one end to the diaphragm, whilst it has a blunt nail at the other end, which is placed on the lead sheath of the faulty cable. Naturally, such a rough method will work only when the ionization is much greater than it ever should be.

If ionization is taking place in the body of a dielectric, the supply current will vary because of the impulse nature of the ionization. If a telephone is supplied with some of the current, a crackling or popping noise will be heard. This method also is very rough, and suffers from the disadvantage that irregularities and harmonics in the supply and discharges from the high-voltage parts of the supply system will produce noises that make the method quite useless.

* See D. M. ROBINSON: "The Breakdown Mechanism of Impregnated Paper Cables," *Journal I.E.E.*, 1935, vol. 77, p. 90; also L. G. BRAZIER: "The Breakdown of Cables by Thermal Instability," *ibid.*, 1935, vol. 77, p. 104.

The problem of detecting the ionization has been seriously tackled in America* by a number of methods. Some of these methods involve tuning at selected frequencies, and the results, though illuminating, are qualitative only.

The present authors started work on the problem in 1931. The first attempt employed a bridge, balanced at 50 cycles per sec., of the form shown in Fig. 1. The vibration galvanometer G is tuned to 50 cycles per sec. and indicates when the supply current is balanced out. The galvanometer is connected across the secondary of a screened transformer, which also feeds a high-pass filter of cut-off frequency 2 000 cycles per sec., followed by an amplifier-detector. The reading of the micro-ammeter A is considered to give some indication of the ionization.

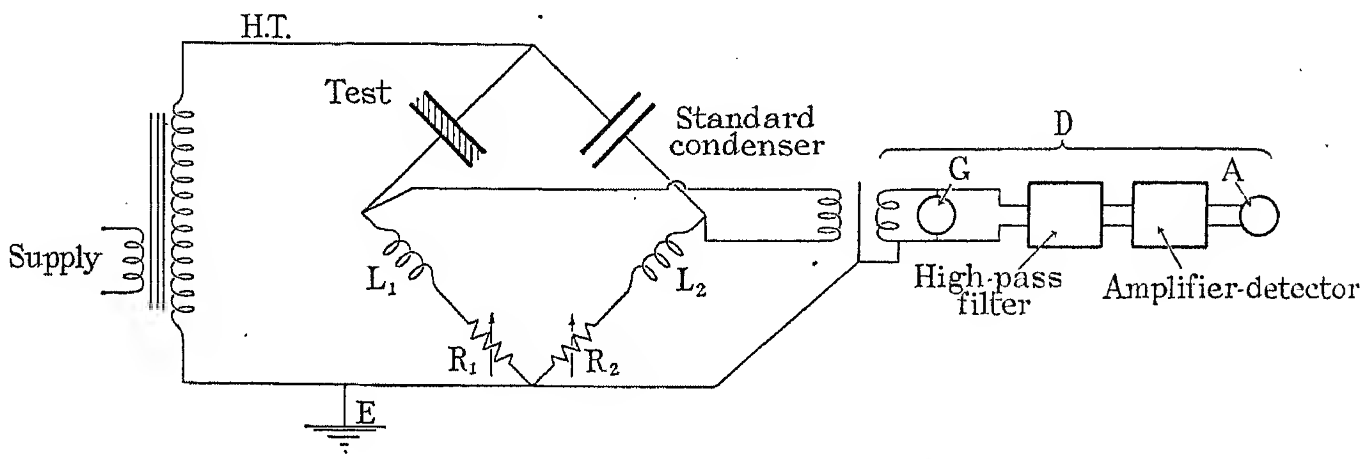

Fig. 1

This bridge arrangement was meant to give a high sensitivity to the high-frequency currents, and it achieved this object. Thus when the low-voltage arms L_1, R_1, and L_2, R_2, were replaced by the arms of the normal Schering bridge, the detected high-frequency current was reduced to one-fourth in a particular case.

The bridge described above was abandoned because of the difficulty of balancing. If L_1 and L_2 are fixed and R_1 and R_2 varied, it is very difficult to find the balanced position: for with any value of R_1 there is a minimum out-of-balance for some value of R_2 far removed from the value required for real balance. It is necessary to vary R_1 and R_2 simultaneously so that they have approximately the ratio $R_1/R_2 = C_2/C_1$. If L_1/L_2 is not nearly equal to C_2/C_1, then R_1 and R_2 may require to be much higher than is convenient. This difficulty can be avoided by keeping R_2 fixed, making $L_2 = 0$, and varying L_1 and R_1. The range over which L_1 must vary with different test condensers makes the method impracticable. The open magnetic field of a variometer is also a disadvantage. It was considered that the effective inductance of L_1 could be varied by placing a variable resistance across it: this procedure immediately reduces the sensitivity to high frequencies, although the arrangement is still better than the Schering bridge.

The main disadvantages of this method are, however, that the use of inductances in the circuit makes it impossible to achieve quantitative results; and also that any external discharges such as occur in the supply transformer and between the high-voltage system and earth, intrude into the measurements.

Moreover, the method of balancing out the 50-cycle current seems unnecessary. A new high-pass filter was made with a cut-off frequency of 4 500 cycles per sec. and this attenuated the 50-cycle current very greatly. Direct measurements could then be made according to the scheme of Fig. 2(*a*): T is a screened, high-frequency, air-core transformer, with a low primary impedance to 50-cycle currents. This arrangement was simplified by replacing the transformer T by an inductive shunt S, as in Fig. 2(*b*); the shunt is required only when the charging current is very high, say more than 1 ampere. For smaller charging currents the shunt can be omitted, and the very simple arrangement of Fig. 2(*c*) results.

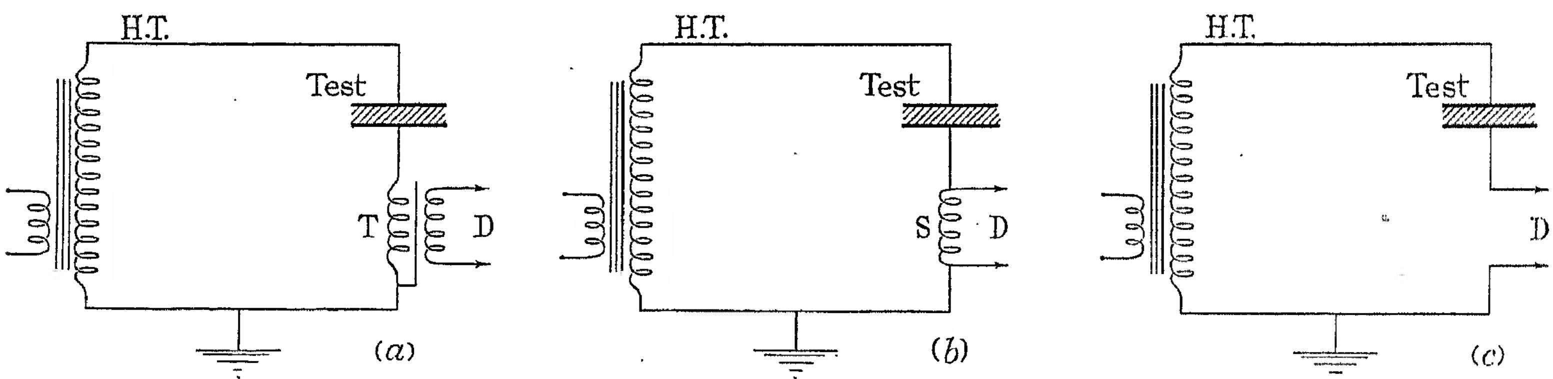

Fig. 2

* J. T. TYKOCINER, H. A. BROWN, and E. B. PAINE: "Oscillations due to Ionization in Dielectrics, and Methods of their Detection and Measurement," *University of Illinois Bulletins*, 1933, vol. 30, Nos. 49 and 50.

EXTERNAL DISCHARGES

The above methods of measurement are quite satisfactory, provided the whole of the h.t. system is itself free from discharge, but discharges occurring from h.t. connections or in the test-transformer secondary winding give rise to high-frequency currents which are measured by the detector. Freedom from such extraneous disturbances can be fairly easily obtained when working on small dielectric samples at moderate voltages (say, up to 10 kV), but this immunity cannot be relied upon in more general use on cables, insulators, etc., at high voltages. Steps must therefore be taken to eliminate the effects of such unwanted discharges as occur.

Production of Artificial Discharges

In order to make experiments on the effect of discharges in various parts of the circuit several methods of generating such discharges at will have been devised. One very simple method consists of a suitable number (dependent on the voltage range to be covered) of sheets of varnished cambric or similar material laid on a flat plate of 3 in. diameter which forms the low-voltage electrode. A second electrode consisting of a flat-ended cylinder of 1·5 in. diameter is placed on the top of the sheets and is connected to the high-voltage side. When sufficient voltage is applied between the electrodes, discharges occur at the edges of the high-voltage electrode. The low-voltage electrode can be connected either to the low-voltage terminal of the sample under investigation (thus representing discharge in the sample), or direct to earth (to represent discharges from the high-voltage system). This simple device has been most useful in producing artificial discharges where required.

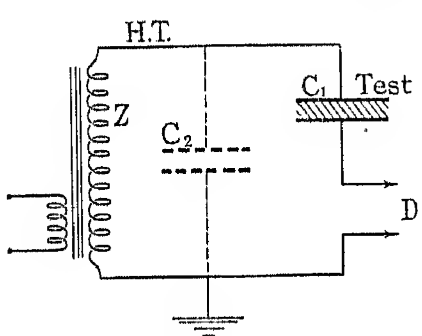

Fig. 3

Use of Shunting Condenser to Locate Discharges

A simple method is available for finding whether a measured discharge is occurring in the test sample itself or externally. A measurement is taken as described above and then a condenser (which must itself be free from discharge at the voltage concerned) is connected between the h.t. supply and earth, and it is noted whether the discharge reading is increased or decreased by so doing. Fig. 3 shows the circuit involved. If the discharge originates in the test sample C_1 the high-frequency current which is measured has to flow through the transformer winding Z. Addition of the extra capacitance C_2 reduces the impedance to this current, so that an increase in the measured discharge current will result. If, on the other hand, the discharge is occurring between the h.t. system and earth it has two paths available, (*a*) through the transformer winding, and (*b*) through the test sample and detector. Reducing the impedance of the transformer by addition of C_2 will in this case reduce the current flowing through the detector.

That this actually occurs in practice has been shown by several experiments made at voltages of only a few kilovolts (so that no uncontrolled discharges occurred), the discharges being introduced artificially by means of the device described above.

METHODS OF ELIMINATING EFFECTS OF EXTERNAL DISCHARGES

It is much more satisfactory to arrange the apparatus so that discharges occurring external to the dielectric under test do not affect the detector, and several ways of doing this have been tried. All these methods involve the use of a second condenser which is known to be free from discharge. Unwanted high-frequency currents pass through this condenser and the test sample in parallel, and are balanced against one another.

Balanced-transformer Method

The first method was developed from the "direct" method of discharge measurement of Fig. 2(*a*). The arrangement is shown in Fig. 4. Two similar, balanced and screened, radio-frequency transformers have their primaries connected in the leads from the test and the standard capacitance respectively. Their secondaries are connected in opposition and in series with the filter input, the output voltage of the transformer in the test-lead being adjustable by means of the potentiometer shown. To balance the arrangement an artificial discharge gap is connected between the high-tension lead and earth, and a potential difference of a few kilovolts is applied to the system. The potentiometer is then adjusted until no deflection is produced on the detector. The discharge gap must be so selected that vigorous discharge will occur across it before there is any possibility of discharge occurring in the test sample itself. After the circuit has been balanced the discharge gap is removed, and the balancing controls are thereafter left untouched. Voltage is then again applied and is increased to the value at which measurements on the sample are required. Any discharges on the h.t. system will be balanced out in the same way as was the artificially-produced discharge; but, when the sample itself discharges, the circulating current causes secondary e.m.f.'s which aid each other, and the detector shows a deflection. Great difficulty was experienced in the

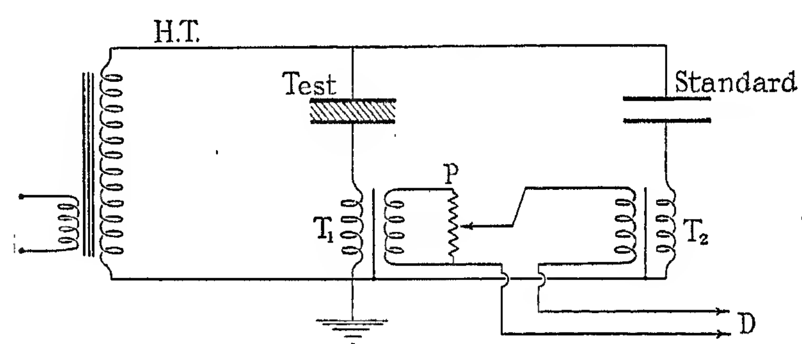

Fig. 4

design of transformers for this purpose because of external pick-up, balancing of stray capacitances, and the varying load on the one transformer caused by the potentiometer adjustment. In practice it was found that unless the test capacitance and the standard capacitance were nearly of the same magnitude a complete balance of external discharge was not possible. The deflection could be reduced to a minimum, and the point at which the sample discharge commenced could often be estimated, but the arrangement was not considered satisfactory.

High-frequency Bridge Method

In view of the desirability of making quantitative measurements, it was considered advisable to keep the circuit as aperiodic as possible. The network shown in Fig. 5 was therefore used. Instead of the e.m.f.'s of two transformers being balanced, the voltage-drops across two resistances are balanced exactly as in an ordinary capacitance bridge. The arrangement is, in fact, similar to the well-known Schering high-voltage bridge, but the bridge is balanced to the high-frequency discharge currents produced by the external gap, and not to the

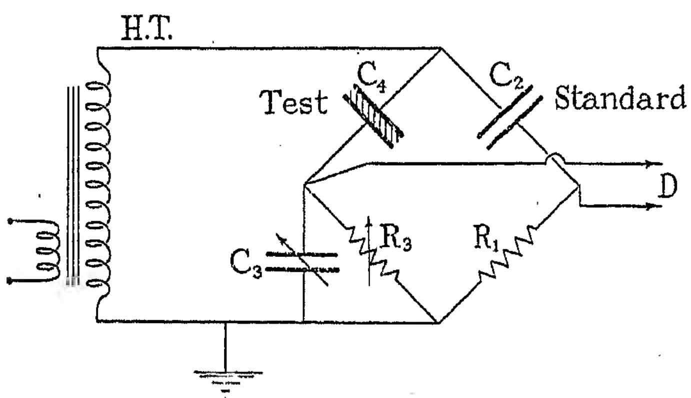

Fig. 5

supply current of 50 cycles per sec. The " p.f. condenser " used in the normal Schering bridge is absent in this arrangement because the capacitance required to balance the power factor of the test sample is very small at these frequencies. On the other hand, if, as is often the case, the capacitance of the test is considerably larger than that of the balancing condenser, a large capacitance (C_3) is required across arm R_3 to compensate for the capacitance of the screened lead on the other side of the bridge. It should be noted that any 50-cycle out-of-balance due to the power factor of the test sample must be completely eliminated by the filter preceding the amplifier.

Sensitivity is achieved by choosing higher values for the ratio arms R_1 and R_3 than are employed in Schering-bridge practice. This can be done, because in balancing we are not concerned with measurement but merely with an elimination, and errors due to lead capacitances do not arise. Thus R_1, the resistance in series with the discharge-free condenser C_2, can conveniently be 5 000 or 10 000 ohms, or even higher. The condenser C_2 is a standard air condenser. Dielectric losses in C_2 can, however, be tolerated so long as they are not due to discharge.

The above arrangement has proved very satisfactory and has been extensively used by the authors. It has been found possible to make discharge measurements on cable samples, etc., with quite heavy external discharges occurring. It should be noted that by providing the sample with a guard system connected to earth, all edge discharges (which are extremely difficult to avoid completely) are balanced out with the other unwanted disturbances.

Bridge Measurements on Earthed Cables

When it is required to make discharge measurements on buried cables the balanced bridge described above is not effective. The conditions are now as shown in

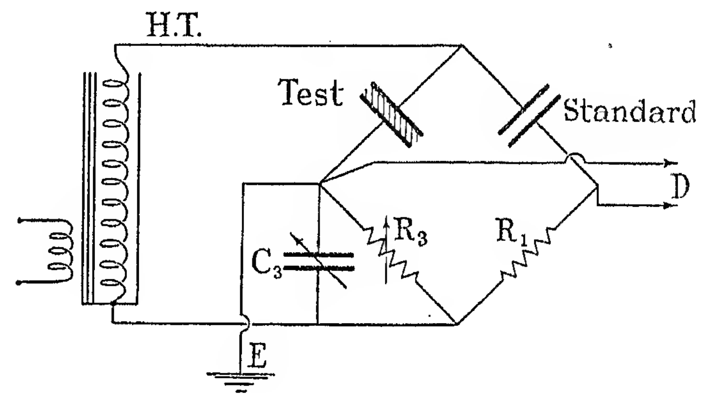

Fig. 6

Fig. 6. It is at once clear that discharges from the h.t. system to earth are in parallel with the test and will be included in the measurement. Two methods of overcoming this difficulty may be considered.

Inverted-bridge Method.

First, the bridge can be inverted as indicated in Fig. 7. This involves placing the resistance balancing-arms, balancing condenser, filter, amplifier, and indicating

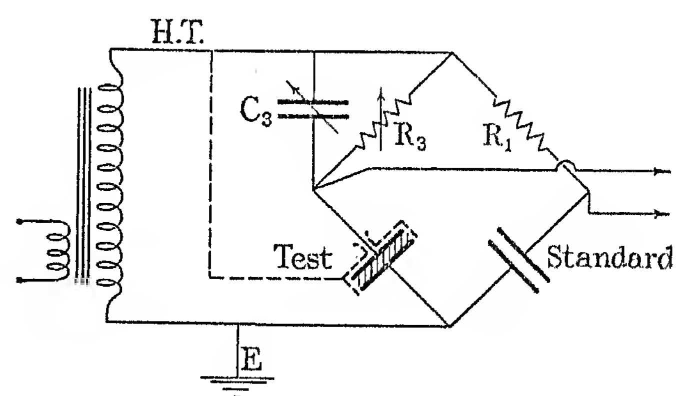

Fig. 7

instrument, all at high voltage. This is not very difficult, and such a unit has been constructed with all the above apparatus (including batteries) mounted inside a metal screening box for hanging on the high-voltage bar. Unfortunately, however, this method fails owing to the great difficulty of making a guard on the end of the cable conductor. The guard required is indicated by the dotted lines in Fig. 7. Consideration of Fig. 8 (a conventional type of cable test end) shows that whilst surface discharges can be guarded by means of a band B (connected to the junction of the resistance arms in Fig. 7) no satisfactory means is available for guarding discharges occurring between C and the conductor. Experience has

shown that such discharges often occur before anything is measurable in the cable itself, so that this method has to be abandoned.

Screened-H.T. Method.

The alternative is to apply the more obvious, but rather unwieldy, method of screening the h.t. leads of the ordinary bridge. The screening is connected to the junction of the resistance arms as shown in Fig. 9, and must be insulated (for low voltage) from earth. The high-voltage transformer must also be provided with an insulated screen connected to the same point.

INTERFERENCE PROBLEMS

Interference is always likely to cause trouble in a.c. bridge work, and in the discharge bridge the problem presents itself perhaps in its most acute form; for not only are the currents concerned of high frequency, but they cover a very wide frequency band on account of their transient nature. The pick-up troubles encountered may be divided into three main groups, as follows:—

(*a*) Direct electrostatic pick-up between the exposed high-voltage connections and the filter, amplifier, etc. This can be eliminated by enclosing these parts in earthed metal cases. It has been found necessary, however, for such screening to be absolutely complete, the smallest projection (such as an unscreened terminal

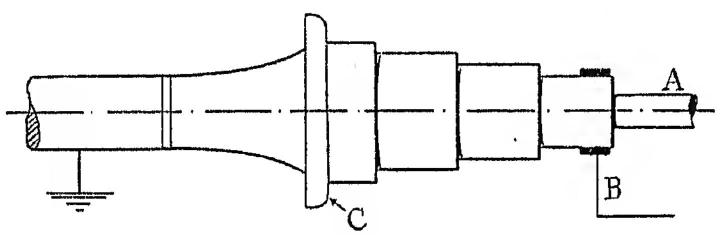

Fig. 8

block, etc.) being sufficient to give rise to considerable deflections of the indicating instrument.

(*b*) Magnetic pick-up between the high-voltage loop and the bridge circuit. This can be avoided by enclosing all the high-voltage connections in shields, the earthing of such shields being so arranged that the conductor and its shield form a concentric " go and return " system.

(*c*) Radiation effects. Radiation from portions of the high-voltage circuit were found very troublesome if the detector was in the vicinity of the test circuit. Shielding the high-voltage connections effects a cure, but it is necessary for such shielding to be very complete. Open-wire mesh screens were found insufficient, the only satisfactory method being the employment of metal tubes. Such screening can, of course, only be applied at moderate voltages. Fortunately, it is found that if the detector be removed 30 or 40 ft. from the test circuit, pick-up due to this cause is not usually serious. To enable this to be done the detector is connected to the test circuit by means of special low-capacitance flexible screened leads.

Earthing.

The usual practice in a high-voltage laboratory is to run a heavy copper strip round the wall of the laboratory and to connect this to an earthing plate at some suitable point. Laboratory apparatus is then connected to this bar when required. This method was not found suitable for the discharge bridge, however, as the impedance of the earth strip was excessive. More effective anchoring was obtained by connecting the detector by a very short wire to the laboratory caging (which has high self-capacitance), or even to a piece of wire netting laid on the floor (either earthed or unearthed).

DESIGN OF THE APPARATUS

Input Transformer

Of interest in connection with the " balanced " models are the balanced and screened transformers used for coupling between the bridge and the filter input. Freedom from external pick-up has been achieved by winding on toroidal cores and by using toroidal electrostatic screens. Cores of the iron-dust type are employed, on account of the high frequencies to be handled. The measurements on a finished transformer were as follows: Primary inductance (1 000 cycles per sec.), 1·01 henrys;

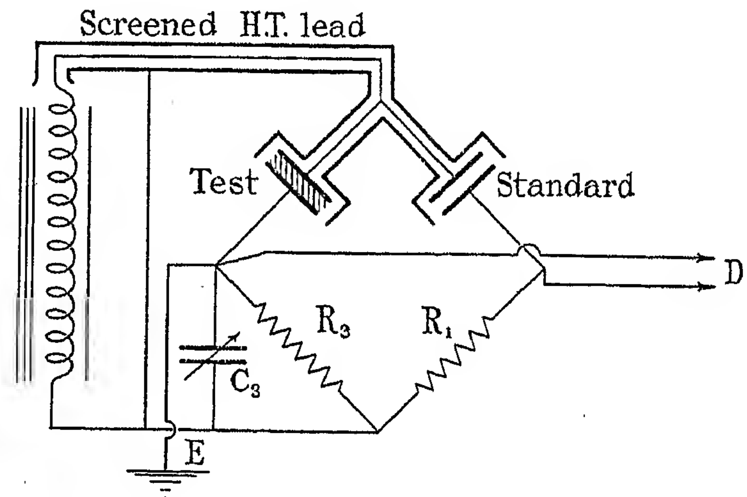

Fig. 9

primary resistance (d.c.), 79 ohms; primary resistance (1 000 cycles per sec.), 166 ohms; primary impedance (10 000 cycles per sec.), 100 000 ohms; voltage ratio, 2:1; secondary inductance (1 000 cycles per sec.), 0·224 henry; secondary resistance (1 000 cycles per sec.), 88·0 ohms.

Filter

The circuit diagram of the high-pass filter is given in Fig. 10. The circuit is of the conventional type, except that special precautions have been taken to eliminate the 5th and 7th harmonics of the 50-cycle supply. Damping resistances are connected across two of the coils and in series with one of the coupling condensers to smooth out humps in the response curve which are otherwise found to occur. The response curve with these resistances connected is shown in Fig. 11.

Amplifier-Detector

The amplifier following the filter is of the ordinary straightforward resistance-capacitance-coupled type. In the first model constructed a cumulative grid detector was employed, and this was connected in a bridge circuit as shown in Fig. 12(*a*).

With no input to the detector, R_1 is adjusted so that no current flows in the galvanometer. In this way the normal plate current of the valve is eliminated and a

deflection is produced when a high-frequency voltage is applied to the valve input. This circuit gives good results and is sensitive, but it suffers from zero fluctuations when operated from the mains, owing to voltage-changes in the latter. This necessitates a fresh balance being made immediately before taking each reading. Some improvement can be made by using a similar valve in place of R_3, but complete matching is difficult.

on a fixed h.t. system which is free from discharge up to about 10 kV.

(*b*) A mains-operated transportable equipment working on the balanced principle of Fig. 5, the whole apparatus being mounted on a laboratory trolley.

(*c*) A battery-operated, balanced equipment, completely self-contained in a portable cabinet.

Unit (*c*) contains a further improvement in the form

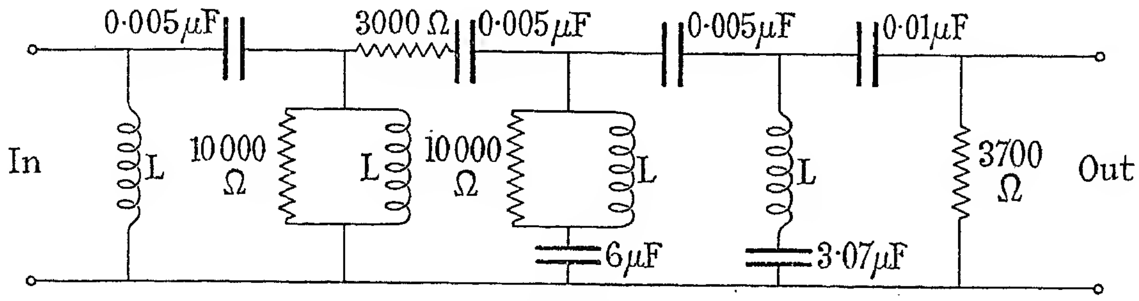

Fig. 10

Inductance of L, 68 mH; resistance of L, 68 ohms.

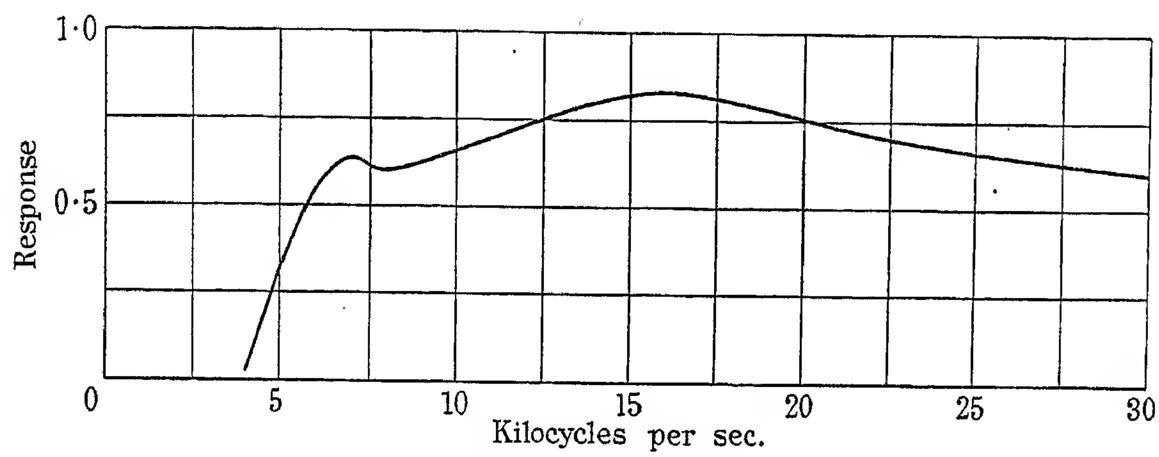

Fig. 11—Response curve of high-pass filter.

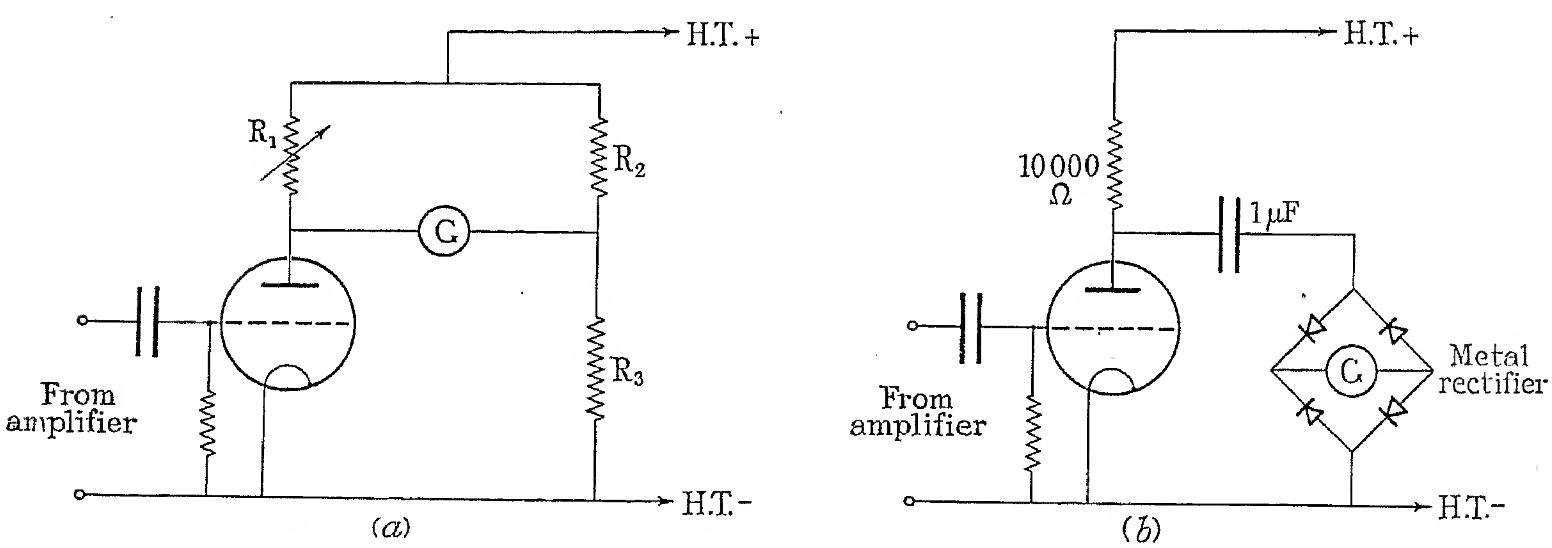

Fig. 12

In the more recent models a full-wave metal rectifier (Type MBS10) has been used, as shown in Fig. 12(*b*). To make up for the loss of sensitivity a third amplifying valve is used.

The following three complete sets of apparatus have been made up and used in experimental work on dielectric samples and cables.

(*a*) A mains-operated set working on the "direct" system of Fig. 2(*c*). This is used for dielectric samples

of a band-pass filter in place of the high-pass filter previously fitted. On account of the test capacitance having a power factor, the high-frequency bridge can theoretically only be balanced at one particular frequency. By narrowing down the band of frequencies passed on to the detector, a more complete balance is obtained. The band width is actually chosen so that with the maximum external discharge likely to be encountered the amount of out-of-balance current

reaching the detector is negligible. A constant-K type filter passing a 10-kilocycle band (from 11 600 to 21 600 cycles per sec.) was constructed, toroidal coils being used to eliminate pick-up between sections.

QUANTITATIVE ANALYSIS OF RESULTS

Hitherto, discharge measurements have been only qualitative. An attempt will now be made to analyse the results quantitatively, so that the severity of a discharge can be calculated after the measuring circuit has been allowed for.

Discharge Current

The 50-cycle voltage is supplied to the dielectric by the transformer, but the discharge e.m.f. occurs inside the dielectric. Suppose the discharging space gives rise to an e.m.f. E acting in series with a capacitance C. The latter is shunted by the capacitance C_4' of the rest of the dielectric, so that the high-frequency e.m.f. measured across the terminals of the test capacitance (on open circuit) would be

$$e = E\frac{C}{C + C_4'} = E\frac{C}{C_4} \quad . \quad . \quad . \quad . \quad (1)$$

where C_4 = total capacitance of sample $= C + C_4'$.

The discharge current in the space is given by

$$i = EpC \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

where $$p = \frac{d}{dt}$$

Equation (1) shows that $i = epC_4$.

We can measure e and C_4, but not C; so that we can measure the discharge current but not the e.m.f. This means that we cannot differentiate between a large discharge e.m.f. generated in a small section of the dielectric and a small discharge e.m.f. originating in a large volume of the dielectric.

Sensitivity of the Direct Method

It is shown in Appendix I that the discharge current in the dielectric is given by

$$i = Av \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where v = voltage at input of filter,

$$\left.\begin{aligned} A &= \left(1 + \frac{Z_5 + Z_6}{Z_4}\right)/Z_5 \\ Z_4 &= \text{impedance of test condenser,} \\ Z_5 &= \text{impedance of parallel combination of filter and stray capacitance } C_5, \\ \text{and } Z_6 &= \text{impedance of parallel combination of h.t. transformer and stray capacitance } C_6 \end{aligned}\right\} \quad (3)$$

When the test condenser has a capacitance of 500 $\mu\mu$F,

$$A = 5{\cdot}2 \times 10^{-4} \quad . \quad . \quad . \quad . \quad (4a)$$

whilst, when the capacitance is 2 500 $\mu\mu$F,

$$A = 8{\cdot}0 \times 10^{-4} \quad . \quad . \quad . \quad . \quad (4b)$$

Sensitivity of the Bridge Arrangement (Balanced Method)

The sensitivity of the balanced bridge arrangement shown in Fig. 13 is also worked out in Appendix I. C_4 is the test capacitance, and may vary between 200 and 3 000 $\mu\mu$F. We assume that the discharge e.m.f. is produced in this arm and is represented by e, as before. C_2 is the high-voltage standard condenser (supposed discharge-free), usually of value 50, 100, or 250 $\mu\mu$F. The other impedances are shown in the figure and explained in Appendix I. An output transformer with a 2:1 stepdown ratio is employed, in order to match conditions as far as possible.

The value of A in equation (2) is given by

$$A = 5{\cdot}4 \times 10^{-4}\left(1 + a\frac{C_4}{C_2}\right) \quad . \quad . \quad . \quad (5)$$

$$\left.\begin{aligned} &\text{where} \quad a = 2{\cdot}5 \text{ when } Z_1 = 10\,000 \text{ ohms} \\ &\text{and} \quad a = 4{\cdot}0 \text{ when } Z_1 = 5\,000 \text{ ohms} \end{aligned}\right\} \quad (6)$$

There are two points to remember. Firstly, the sensitivity of the bridge is inversely proportional to A, since the voltage input to the filter is the discharge

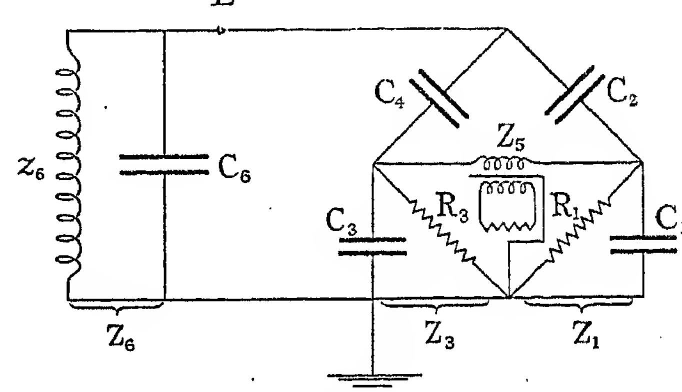

Fig. 13

current divided by A. Secondly, since A is only slightly dependent on frequency, the bridge is aperiodic within the range of frequencies accepted by the filter and detector.

Effect of Circuit Conditions on Sensitivity

If the bridge is balanced to external discharge, the impedance of the supply transformer and parallel-connected loads is of no importance. The insertion of a choke or resistance in the h.t. lead (at L, Fig. 13) should have no effect, except in a secondary way by influencing the frequency of the discharge currents.

If the test capacitance is large compared with the standard capacitance, (5) reduces to

$$A = 5{\cdot}4 \times 10^{-4}\frac{aC_4}{C_2} \quad . \quad . \quad . \quad . \quad (5a)$$

showing that the sensitivity is inversely proportional to the test capacitance.

If, however, ionization is occurring uniformly along the length of the cable, the current i is proportional to the length and hence to C_4, so that the sensitivity is unaffected by the test capacitance. If, on the other hand, the ionization is local, the sensitivity is inversely proportional to the test capacitance, as stated.

CALIBRATIONS

Appendix II shows that within the frequency range of the instrument the discharge current consists of frequencies which are odd multiples of 50 cycles per sec., the amplitudes of these waves being all equal. Thus the frequency spectrum consists of equal lines, equally spaced. An account will now be given of how the calibrations must be used to measure this current.

It was first shown that the rectifier, following the filter and amplifier, was aperiodic and measured the r.m.s. value of any combination of applied waves, although the reading was not proportional to the r.m.s. value. These two facts were established in the way shown in Appendix III. A frequency is then chosen in the range accepted by the filter-amplifier-detector as a basic frequency. It is convenient that this frequency should have the maximum response, but this is not essential. From the calibrations a constant k is calculated (with this frequency as the base), k being a band-width factor of the apparatus. In an ideal arrangement, with a rectangular response curve, k is proportional to the square root of the band width. From the response curve

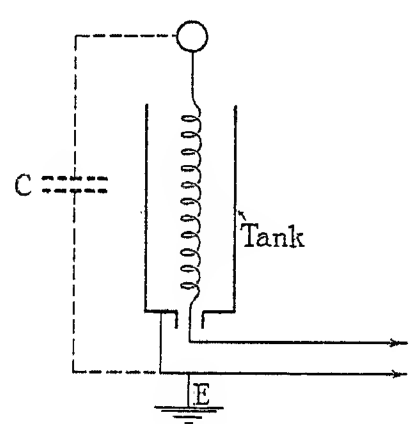

Fig. 14

of waves of the basic frequency we read off a voltage e_0 corresponding to the observed deflection. Then the amplitude of the waves in the discharge current is given by

$$i_0 = \frac{e_0 A}{k} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

DISCHARGES ON HIGH-VOLTAGE TRANSFORMERS AND APPARATUS

One of the first tests required on any high-voltage equipment to be used for discharge measurements is to find the voltage at which the high-voltage transformer, busbars, etc., themselves commence to discharge. For measurements by the " direct method " this is essential, as it limits the voltage at which reliable results can be obtained. The knowledge is also desirable for the balanced method in case the balancing has not been accurately accomplished. Any measured discharge which commences at the same voltage as that at which transformer discharge starts should be regarded with suspicion until it has been ascertained beyond doubt that the bridge has been correctly and completely balanced.

The method of making the discharge measurement on a testing transformer is indicated in Fig. 14. It is necessary for the low-tension end of the high-voltage winding to be insulated from the tank (and screens, if present). The detector input is then connected between this point and the earthed tank. It is clear that any discharges occurring from the winding to the tank, to screen or to earth, or between sections of the winding, will cause a high-frequency current to flow in the filter input. After the transformer has been tested alone, the high-voltage busbar can be connected and the test repeated. It has been found that testing transformers generally show discharges at voltages very much below their rated maximum. In the case of very high-voltage equipments, discharges may occur at voltages as low as 30 per cent of the maximum.

MEASUREMENTS MADE WITH THE DISCHARGE BRIDGE

The detector in its various forms has been extensively used in connection with researches on dielectrics of all kinds, and on cable. In some cases the apparatus has given little information which could not be gleaned

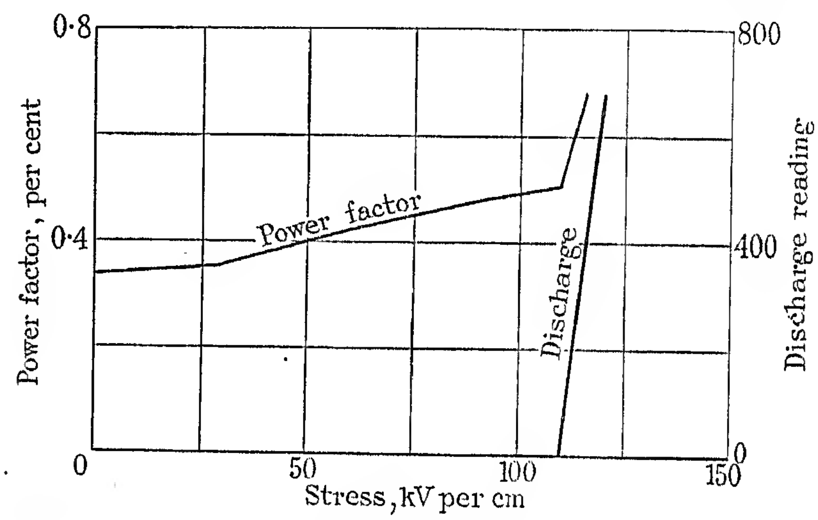

Fig. 15—Power factor and discharge of impregnated-paper condenser sample.

from the p.f. measurements alone, but in many others the discharge detector has thrown much light on the phenomena occurring in the dielectric. So many tests have been carried out that it is not possible to record them all here, but it is proposed to describe a few examples to demonstrate the utility of the instrument.

Differentiation Between True Ionization and Rise of Power Factor Due to Other Causes

The discharge bridge, in conjunction with the Schering bridge, enables us to determine whether an increase in p.f. is due to gaseous ionization or not.

By arranging the low-voltage connections to the test condenser and the standard condenser to pass through a special double-pole change-over switch (designed so as to make on one side before breaking on the other), the test can be transferred from the 50-cycle p.f. bridge to the discharge bridge without interrupting the high-voltage supply. In this way the two measurements can be taken nearly simultaneously, often with illuminating results. Many cases have been found where increases of p.f. (hitherto attributed to gaseous ionization) have occurred without any measurable discharge being present. An example of such a case is shown in Fig. 15.

There are many possible causes for the rising p.f.

characteristic, but one of the most important has been found to be the presence of moisture. Indeed it seems possible, from results obtained by the authors and other experimenters, that this may prove to be one of the most sensitive electrical tests for moisture in a dielectric. Considerably more work will be necessary, however, before it can be firmly established.

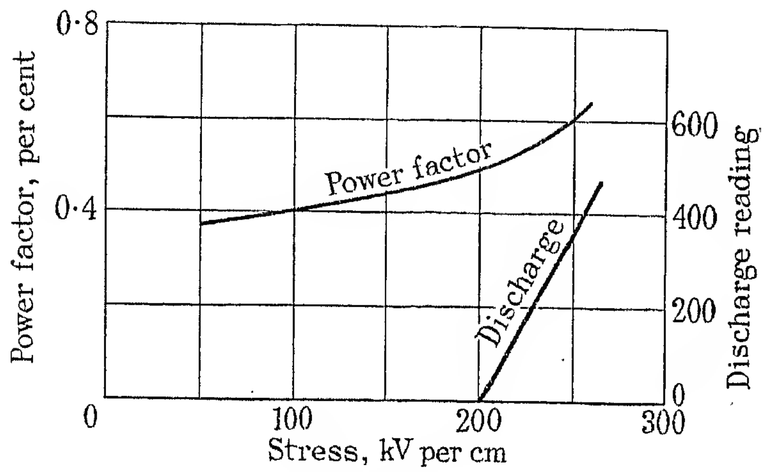

Fig. 16—Curves for impregnated-paper condenser sample.

Detection of Discharges Not Shown up by Power-factor Measurement

A p.f./stress curve, as taken on the 50-cycle Schering bridge, often gives indefinite results from which it is not possible to estimate the ionization point with accuracy. A particularly good example of such a curve, for an impregnated-paper condenser sample, is reproduced in Fig. 16. The discharge curve which is shown in the same figure fixes the ionization point definitely.

Utility of Balanced-Bridge Method

The necessity for using the balanced-bridge method at the higher voltages is clearly demonstrated by the example in Fig. 17, which shows discharge measurements taken on a cable sample by the two methods. From the results given by the direct method it would appear that discharge started in the dielectric at 40 kV, but by using the balanced method the starting point was shown to be as high as 70 kV. Investigation proved that the discharge previously measured at 40 kV was occurring in the testing transformer.

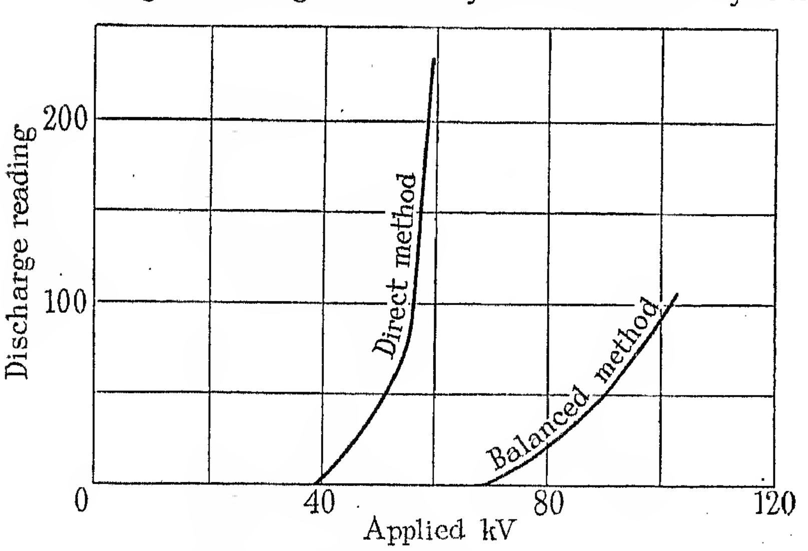

Fig. 17—Direct and balanced discharge measurements on 66-kV cable sample.

CHANGES OF DISCHARGE WITH TIME

It has been found that discharge in dielectrics often changes with time. Usually a comparatively rapid change takes place during the first hour or so after voltage has been applied, and the discharge then settles down to a more or less steady value. A further very slow change is observed with some dielectrics, often extending over days and sometimes weeks.

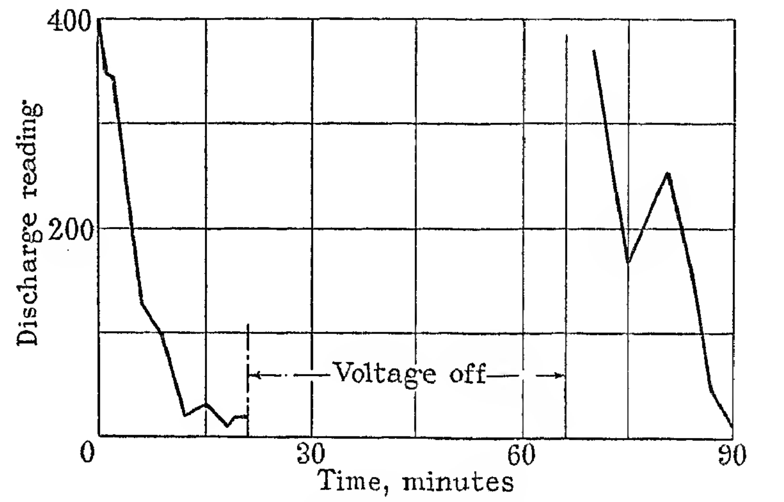

Fig. 18—Fall of discharge with time on undried varnished-paper cable.

Examples of the former change are given in Figs. 18 and 19. Fig. 18 shows how the discharge current in a cable sample insulated with varnished paper falls rapidly with time. After the voltage has been switched off for some time the rapid fall is repeated. Fig. 19 shows the results on an exactly similar cable which had been subjected to a vacuum drying process. Although the voltage in this test was higher, the discharge current is very much less, as is also the fall with time. It seems, therefore, that moisture very materially affects the discharge as well as the p.f./voltage characteristic.

An example of the prolonged slow change with time is given in Fig. 20. This curve was taken on an impregnated-paper dielectric, the sample being in the form of a flat-plate condenser with a guard ring. It shows a gradual fall of discharge extending over 650 hours, after which the discharge vanished. No further discharge occurred, and after 900 hours the test was stopped and the condenser examined. A considerable amount of wax and some carbonized matter had formed in the gap between the guard ring and the measuring plate of the condenser. It is clear that this guard-ring gap (which

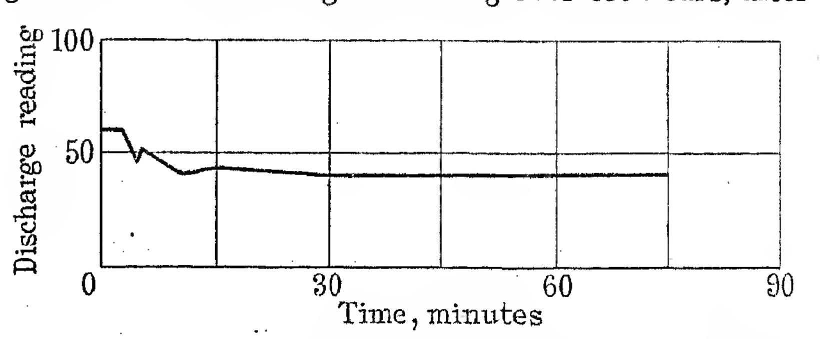

Fig. 19—Fall of discharge with time on dried varnished-paper cable.

was too wide) caused vigorous local discharge and that the carbon thus formed filled the gap and, in time, so modified the stress that no further discharge occurred. It is to be noted, however, that had the initial ionization occurred in such a manner that the carbon formed a spear-head into the dielectric the discharge would undoubtedly have become greater with time and eventually have caused breakdown of the sample. It is specially interesting that the method enabled changes of discharge to be measured, the discharge being so localized as to leave the p.f. unchanged.

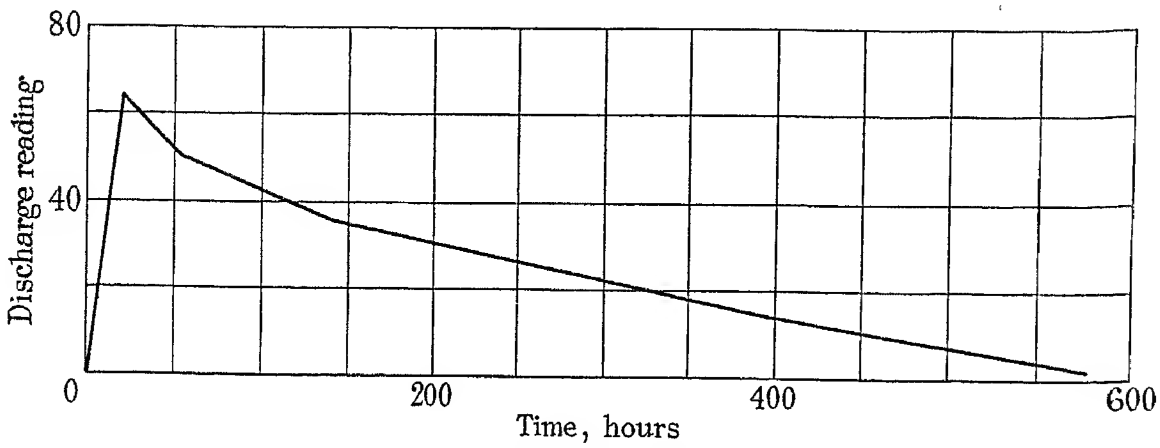

Fig. 20—Fall of discharge with time on impregnated-paper condenser.

COMPARISONS OF DISCHARGES WITH A.C. AND D.C. VOLTAGES

The superior performance on direct current of dielectrics, supporting insulators, etc., is well known. The explanation usually put forward is that, since with direct current there are no losses except that due to conduction, less heat is generated in the dielectric. That another cause is also to be found in the freedom from discharge with direct current is demonstrated by the following tests.

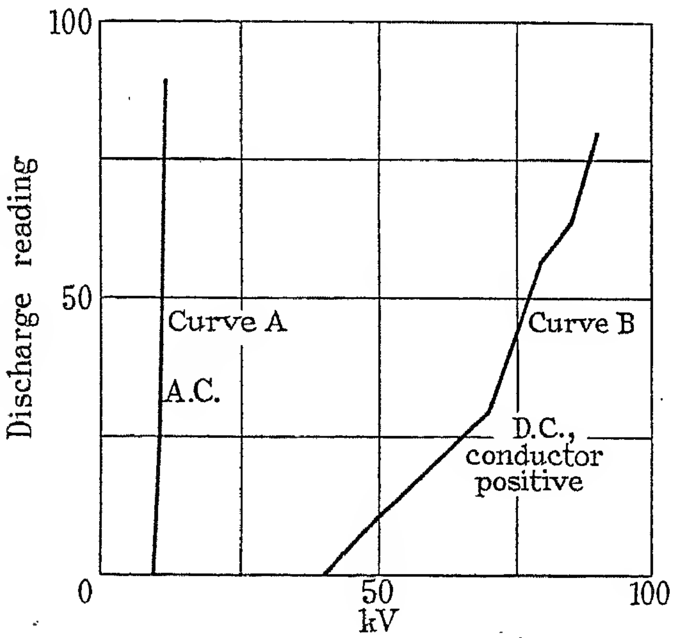

Fig. 21—Discharge on 66-kV cable with plain cut-back ends.

A short length of 66-kV cable had its sheath cut back about 12 in. at each end. An a.c. voltage was first applied, and resulted in heavy visible discharges occurring at the edges of the cut-back sheath. The discharges were measured (using the balanced method, to eliminate external discharges) and found to commence at 11 kV and to increase so rapidly as to overload the detector at 15 kV (curve A, Fig. 21). A d.c. voltage was next applied, with the conductor negative. Although the applied voltage was d.c., the balancing bridge was still used; for it must be remembered that the purpose of this bridge is to balance out unwanted high frequencies, caused by discharge, from the high-voltage connecting wires, etc. The negative voltage on the conductor was increased to 100 kV without any discharge whatever being detected.

Bearing in mind the extreme sensitivity of the apparatus used, the result is noteworthy. With the conductor positive, discharge commenced at 45 kV (curve B, Fig. 21).

These results seem to contradict the well-known fact that a conductor at negative potential gives more corona loss than one at the same, but positive, potential. It was therefore suspected that the discharges measured with the conductor positive were occurring at the cut-back sheath, which, of course, was negative. This was confirmed experimentally by putting earthed guard-

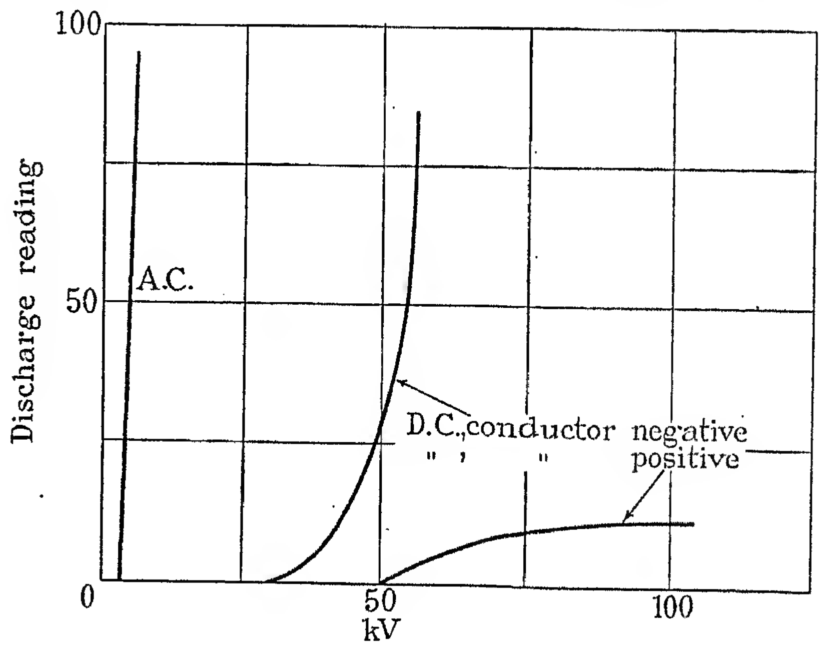

Fig. 22—Discharge on 0·1-in. wall cable with guarded ends.

rings at the cut-back ends of the sheath. A thinner-walled cable was used for this experiment, so that, with the apparatus available, discharges could be obtained with conductor either negative or positive. The results thus obtained are shown in Fig. 22.

The discharge detector is a useful instrument which can be used, in certain cases, in the design of joints, sealing ends, and similar apparatus. By making up experimental models with suitably sectionalized electrodes and then taking discharge measurements with both polarities, the seat of internal discharges can be located.

EFFECT OF STRANDING ON IONIZATION VOLTAGE

Alternating-current measurements have been carried out on unimpregnated cables made with ordinary stranded conductors and also with lead-sheathed conductors of the same overall diameter. Unimpregnated cables were used to avoid irregularities of impregnation and obtain a more or less uniform system of voids. The conductor consisted of 37 strands of 0·083-in. diameter wires, and the thickness of the dielectric wall was 0·515 in. The voltages at which ionization set in, with the two cables under identical pressure and temperature conditions, were: plain stranded conductor, 18 kV; lead-covered conductor, 24 kV.

These give a stranding factor of 1·33, in agreement with the factor of 1·35 calculated from the expression obtained by Levi Civita in 1905.* This in itself is an interesting demonstration, but it also provides confirmation of the view that ionization first makes its appearance at the conductor. Voids in the body of the dielectric would be expected to be independent of the stranding. The large difference between the d.c. discharges measured with the conductor positive and negative provide still further confirmation of the above.

Acknowledgments

In conclusion, the authors wish to thank Messrs. Callender's Cable and Construction Co., Ltd., for permission to publish this work and for the facilities provided for the experiments, which were carried out in the Company's research laboratories. They also acknowledge the assistance of Mr. N. Westcombe in connection with the many calibrations and other measurements involved.

APPENDIX I

Sensitivity of Direct Method

The circuit diagram, including unavoidable stray capacitances, is shown in Fig. 23. Z_4 is the impedance of the test condenser, of capacitance C_4. Z_5 is the parallel combination of the filter input impedance z_5 (3 700 ohms pure) and the lead capacitance C_5 (about 1 000 $\mu\mu$F). Z_6 is the parallel combination of the transformer impedance z_6 and any parallel-load and busbar capacitances C_6.

The discharge current is given by

$$I = \frac{e}{Z_4 + Z_5 + Z_6}$$

where e is the discharge e.m.f. in series with C_4, given by equation (1). We have, therefore,

$$\begin{aligned} I &= \frac{EC}{C_4}\,\frac{1}{Z_4+Z_5+Z_6} \\ &= \frac{EpC}{pC_4}\,\frac{1}{Z_4+Z_5+Z_6}, \quad \text{where} \quad p \equiv \frac{d}{dt} \\ &= EpC\,\frac{z_4}{Z_4+Z_5+Z_6} \end{aligned}$$

We have used $p \equiv d/dt$ instead of $j\omega$, as the wave may not be sinusoidal. $1/(pC_4)$ is Z_4. Also EpC is the discharge current in the cavity, and has been called i. We have, then,

$$I = i/\left(1 + \frac{Z_5}{Z_4} + \frac{Z_6}{Z_4}\right)$$

Supposing the voltage at the input of the filter is v, we have

$$v = IZ_5$$

giving $$i = Av \qquad (2)$$

where $$A = \left(1 + \frac{Z_5 + Z_6}{Z_4}\right)/Z_5 \qquad (3)$$

The sensitivity depends upon the test capacitance, the lead capacitance C_5, the filter impedance, and also

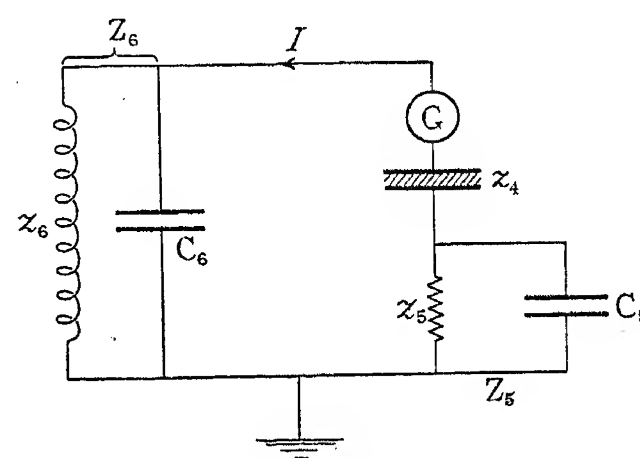

Fig. 23

upon Z_6. The detector-amplifier measures I, from which i, the discharge current proper, can be calculated.

Sensitivity of Standard Laboratory Arrangements.

(i) *Measurements on small condensers.*—The authors have often experimented with condensers of two sizes, namely 500 and 2 500 $\mu\mu$F. In the former case the test capacitance C_4 is about 500 $\mu\mu$F, the screened-lead capacitance C_5 is about 1 000 $\mu\mu$F, the filter impedance is 3 700 ohms, and the busbar capacitance is approximately 500 $\mu\mu$F. The impedance of the transformer has been measured from 8 to 20 kilocycles per sec. The impedance is that of a capacitance of 200 $\mu\mu$F at 10 kilocycles per sec., 500 $\mu\mu$F at 20 kilocycles, and about 700 $\mu\mu$F at 30 kilocycles.

The magnitudes of $\left(1 + \frac{Z_5}{Z_4} + \frac{Z_6}{Z_4}\right)$ at 10, 20, and 30 kilocycles per sec. are 1·74, 1·59, and 1·67 respectively.

Z_5 is the parallel combination of 3 700 ohms and 1 000 $\mu\mu$F, so that $I = Av$, where

$A = 4{\cdot}8 \times 10^{-4}$ at 10 kilocycles,
$4{\cdot}7 \times 10^{-4}$ at 20 kilocycles,
and $6{\cdot}1 \times 10^{-4}$ at 30 kilocycles . (4)

* *Rendiconti del Circolo matematico di Palermo*, 1905, vol. 20, part 1, p. 173.

An average value of $5\cdot 2 \times 10^{-4}$ will be as accurate as we can expect. This formula gives discharge current directly in terms of measured voltage. Thus

$$i = 5\cdot 2 \times 10^{-4}v \quad . \quad . \quad . \quad . \quad (4a)$$

In the case of the larger condensers, the test capacitance is 2 500 $\mu\mu$F, the screened-lead capacitance is 1 000 $\mu\mu$F, the filter impedance is 3 700 ohms, the busbar capacitance is 2 000 $\mu\mu$F, and the transformer impedance is as above. The magnitudes of $\left(1 + \frac{Z_5}{Z_4} + \frac{Z_6}{Z_4}\right)$ at 10, 20, and 30 kilocycles per sec. are 2·32, 2·62, and 3·0 respectively. From these we get $i = Av$, where

$A = 6\cdot 3 \times 10^{-4}$ at 10 kilocycles,
$7\cdot 9 \times 10^{-4}$ at 20 kilocycles,
and $9\cdot 8 \times 10^{-4}$ at 30 kilocycles.

We may assume an average of $A = 8 \times 10^{-4}$, so that

$$i = 8\cdot 0 \times 10^{-4}v \quad . \quad . \quad . \quad . \quad (4b)$$

(ii) *Bridge arrangement* (*balanced method*).—The sensitivity of the discharge bridge with various parallel loads and lead capacitances will now be calculated. The complete diagram, with stray capacitances, is shown in Fig. 13.

C_4 is the test capacitance, which may vary between 200 and 3 000 $\mu\mu$F. The discharge e.m.f. is assumed to be produced in this arm and is represented by e, as before.

C_2 is the high-voltage standard condenser (supposed discharge-free), of value 50, 100, or 250 $\mu\mu$F.

Z_1 comprises a resistance R_1 (value 5 000 or 10 000 ohms) in parallel with the lead capacitance C_1 (value about 500 $\mu\mu$F).

Z_3 is the parallel combination of the variable resistance R_3, and the lead capacitance (= 500 $\mu\mu$F) and balancing condenser C_3.

Z_5 is the impedance presented by a 2:1 stepdown transformer, of primary inductance 1 henry, with the high-pass filter on the secondary side. The impedance of the combination is the parallel combination of $j\omega . 1$, and 14 800 ohms, where $\omega = 2\pi \times$ frequency.

Z_6 is the parallel combination of the transformer secondary impedance z_6 and the other lead capacitances C_6, if any. C_6 may be as high as $0\cdot 1$ μF if several cables are in parallel on the same testing transformer.

The current in the winding connected to the filter is twice the current in the winding connected to the bridge, as a 2:1 stepdown transformer is employed. Thus the current in the filter is given by

$$\left.\begin{aligned} I &= \frac{2eN}{D} \\ &\text{where} \\ N &= Z_6(Z_1 + Z_3) + Z_3(Z_1 + Z_2), \\ &\text{and} \\ D &= Z_6[Z_5(Z_1 + Z_2 + Z_3 + Z_4) + (Z_1 + Z_3)(Z_2 + Z_4)] \\ &\quad + Z_3Z_4(Z_1 + Z_2) + Z_1Z_2(Z_3 + Z_4) \\ &\quad + Z_5(Z_1 + Z_2)(Z_3 + Z_4) \end{aligned}\right\} (8)$$

In the balanced condition, $Z_1Z_4 = Z_2Z_3$. This is achieved by putting an external discharge across Z_6 and balancing out. Substituting $Z_3 = Z_1Z_4/Z_2$ in equations (8), we get

$$I = \frac{2e}{Z_2 + Z_4 + Z_5\left(1 + \frac{Z_2}{Z_1}\right)}$$

$$= \frac{2e}{Z_2 + Z_4 + (Z_5Z_2/Z_1)},$$

as Z_2 is very large compared with Z_1.

Thus
$$I = \frac{2e}{Z_2\left(1 + \frac{Z_4}{Z_2} + \frac{Z_5}{Z_1}\right)} \quad . \quad . \quad . \quad . \quad (9)$$

$$= \frac{2e}{Z_2\left(1 + \frac{C_2}{C_4} + \frac{Z_5}{Z_1}\right)}$$

Equations (1) and (9) give

$$I = \frac{2EC}{C_4}\frac{1}{Z_2\left(1 + \frac{C_2}{C_4} + \frac{Z_5}{Z_1}\right)}$$

If $p \equiv d/dt$, $Z_2 = 1/(pC_2)$. Then

$$I = \frac{2EC}{C_4}\frac{pC_2}{\left(1 + \frac{C_2}{C_4} + \frac{Z_5}{Z_1}\right)}$$

$$= \frac{2EpC}{\frac{C_4}{C_2}\left(1 + \frac{C_2}{C_4} + \frac{Z_5}{Z_1}\right)}$$

$$= \frac{2i}{\frac{C_4}{C_2}\left(1 + \frac{C_2}{C_4} + \frac{Z_5}{Z_1}\right)}$$

$$= \frac{2i}{1 + \frac{C_4}{C_2}\left(1 + \frac{Z_5}{Z_1}\right)} \quad . \quad . \quad . \quad . \quad (10)$$

The sensitivity of the bridge is I/i and depends upon C_2, C_4, Z_1, and Z_5. If we assume that the frequency of discharge is 10 kilocycles per sec. or higher, Z_5 is about 14 800 ohms, slightly inductive; and Z_1 is 5 000 or 10 000 ohms, slightly capacitive: thus Z_5/Z_1 is 3 or 1·5. The discharge current is then given by

$$I = \frac{2i}{1 + a\frac{C_4}{C_2}}, \quad \text{where} \quad a = 1 + \frac{Z_5}{Z_1} \quad . \quad (11)$$

Thus

and
$$\left.\begin{aligned} a &= 2\cdot 5 \text{ when } Z_1 = 10\,000 \text{ ohms} \\ a &= 4\cdot 0 \text{ when } Z_1 = 5\,000 \text{ ohms} \end{aligned}\right\} \quad . \quad . \quad (6)$$

Equation (11) gives

$$\left.\begin{aligned} i &= 5\cdot 4 \times 10^{-4}\left(1 + a\frac{C_4}{C_2}\right)v \\ &= Av \end{aligned}\right\} \quad . \quad . \quad . \quad (5)$$

APPENDIX II

Estimate of the Discharge Currents

It is interesting to attempt to estimate the discharge current, assuming some reasonable mechanism of discharge. Moreover, the estimate is essential in order that we may know how to use the calibration curves of the discharge detection apparatus.

There are two reasonable mechanisms of discharge. Gemant* has shown that in one type of discharge the void sparks over 4 or 8 or 12 times per cycle of the applied wave. The other type occurs when the void is in the body of the dielectric, and therefore in this case the discharge is of the silent or dark kind. We will consider only the latter case, as the majority of voids are in the body of the dielectric.

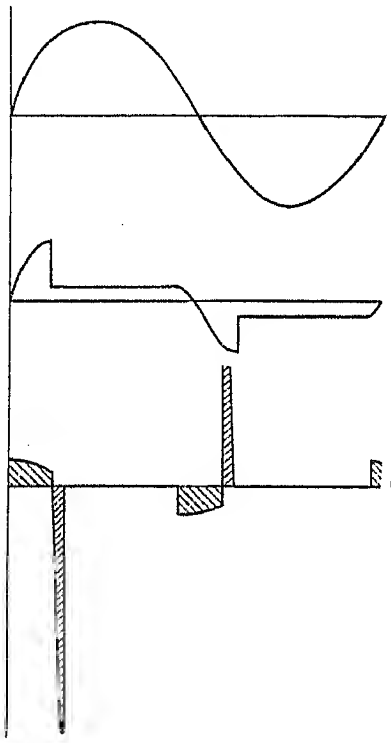

Fig. 24

If the void does not discharge, the voltage across it is as shown in Fig. 24(*a*). If it does discharge, the voltage is as shown in Fig. 24(*b*). Calling the capacitance of the void c and the voltage across it V, the current through it is $c\,dV/dt$; this current is shown in Fig. 24(*c*), for the case of discharge. The voltage rises sinusoidally from zero to V_a (at which value discharge begins), falls to a small voltage V_0 which is required to maintain the discharge, and remains at V_0 until the normal voltage falls to V_0, when the discharge ceases and the voltage is of the normal value. The second half-cycle follows the same procedure. There are four pulses of discharge current, two of very short duration and great amplitude, and two of comparatively long duration and small amplitude. As the first peaky pulse results in a drop of the voltage from V_a to V_0, the area of the pulse is $c(V_a - V_0)$. The second and broader pulse results in a drop of the voltage from V_0 to $-V_a$, so that its area is $c(V_a + V_0)$. The duration of the very short pulse is of the order of 10^{-7} or 10^{-8} sec., whilst that of the longer is $\frac{1}{\omega}$ arc sin $\frac{V_a}{V}$ sec., where $\omega = 2\pi \times 50$ and V is the normal peak voltage applied to the void. The duration of the longer pulse is thus of the order of 3 or 4 milliseconds. We have to find the high-frequency components of these pulses, and it is convenient to consider the short pulses and long pulses separately.

The short pulses represent a periodic function, $f(t)$ say, so that we can put

$$f(t) = \sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t)$$

where
$$a_n = \frac{\omega}{\pi}\int_0^{2\pi/\omega} f(t) \cos n\omega t \,.\, dt$$

and
$$b_n = \frac{\omega}{\pi}\int_0^{2\pi/\omega} f(t) \sin n\omega t \,.\, dt$$

$f(t)$ is zero except near $t = \theta/\omega$, where

$$\theta = \text{arc sin}\,(V_a/V)$$

In this region of t, we have

$$\int f(t)dt = -c(V_a - V_0)$$

Applying this fact, we find that

$$a_n = -\frac{\omega}{\pi}c(V_a - V_0)\cos n\theta + \frac{\omega}{\pi}c(V_a - V_0)\cos n(\pi + \theta)$$

so that
$$a_n = -\frac{2\omega}{\pi}c(V_a - V_0)\cos n\theta \text{ when } n \text{ is odd,}$$

and $a_n = 0$ when n is even.

Similarly
$$b_n = -\frac{2\omega}{\pi}c(V_a - V_0)\sin n\theta \text{ when } n \text{ is odd,}$$

and $b_n = 0$ when n is even.

Substituting in the formula for $f(t)$, we get

$$f(t) = -\frac{2\omega}{\pi}c(V_a - V_0)\left[\cos(\omega t - \theta) + \cos 3(\omega t - \theta) + \cos 5(\omega t - \theta) + \ldots\right]$$

This procedure is legitimate for frequencies which are so low that their period is much greater than 10^{-7} or 10^{-8} sec. Thus the short pulses possess a frequency spectrum consisting of odd multiples of 50 cycles per sec. with equal amplitudes up to 1 million cycles at least. At frequencies above this the spectrum becomes concentrated, but the discharge detector does not respond to such high frequencies.

We may assume, so far as high frequencies are concerned, that the broad pulses are square waves of duration $t = \theta/\omega$, and value

$$c(V_a + V_0) \div \frac{\theta}{\omega} = \frac{\omega c}{\theta}(V_a + V_0)$$

* A. Gemant: "The Loss Curves of Insulating Materials containing Air," *Zeitschrift für Technische Physik*, 1932, vol. 13, p. 184; also A. Gemant and W. von Philippoff: "The Spark-gap with Series Condenser," *ibid.*, 1932, vol. 13, p. 425.

The Fourier series corresponding to these pulses is

$$\frac{4\omega}{\pi}c(V_a+V_0)\frac{1}{\theta}\left[\sin\frac{\theta}{2}\cos\left(\omega t-\frac{\theta}{2}\right)+\frac{1}{3}\sin\frac{3\theta}{2}\cos 3\left(\omega t-\frac{\theta}{2}\right)+\frac{1}{5}\sin\frac{5\theta}{2}\cos 5\left(\omega t-\frac{\theta}{2}\right)+\dots\right].$$

The high-frequency components have small amplitudes: thus the amplitude of the wave of frequency 8 050 cycles per sec. is

$$\frac{4\omega}{\pi}c(V_a+V_0)\frac{1}{161\theta}\sin\frac{161\theta}{2} < \frac{4\omega}{\pi}c(V_a+V_0)\frac{1}{161\theta}$$

The corresponding amplitude in the wave due to the peaky pulses is

$$\frac{2\omega}{\pi}c(V_a-V_0)$$

so that the ratio of the two amplitudes is

$$\frac{2(V_a+V_0)}{(V_a-V_0)}\frac{1}{161\theta}$$

Now V_0 is small compared with V_a, and θ is in the region of $\pi/6$, so that the ratio is about 1/40. Thus, in the band we accept, only the waves in equation (1) are important. We may, without appreciable error, neglect V_0 and the negative sign, and write, for the discharge current in the single void,

$$\frac{2}{\pi}\omega cV_a\left[\cos(\omega t-\theta)+\cos 3(\omega t-\theta)+\cos 5(\omega t-\theta)+\dots\right]$$

The total discharge current is due to a number of such voids of different thicknesses and of different maximum voltages, necessitating a summation for different values of c, V_a, and θ. There seems to be no reason why the uniform character of the spectrum should be much affected by this; exact calculation is too difficult, and so it will be taken as reasonable that the uniform character of the spectrum is not destroyed by this summation. We will therefore say that the total discharge current is

$$i=i_0\left[\cos(\omega t-\theta_1)+\cos 3(\omega t-\theta_3)+\cos 5(\omega t-\theta_5)+\dots\right]$$

APPENDIX III

Calibrations

The first thing to be done was to investigate the behaviour of the rectifier. Some waves of various frequencies and voltages were applied to the primary of the filter input transformer, and the rectified output readings noted (see Fig. 25). It is seen from this figure that for all output readings the ratio of the input voltages for any two given frequencies is a constant. This shows that the variation of response with frequency is due to the combination of transformer, filter, and amplifier, but the rectifier itself is aperiodic.

To show that the rectifier measures r.m.s. values, a voltage of 400 microvolts at 12 000 cycles per sec. was applied, and the reading was found to be 110. The same input at 6 000 cycles per sec. gave a reading of 50. The two waves were then applied in series from separate oscillators, and a reading of 150 obtained. From the curves (Fig. 25), 400 microvolts at 6 000 cycles per sec. is equivalent, as far as the rectifier is concerned, to 250 microvolts at 12 000 cycles per sec. The root-sum-square of 250 and 400 is 471 microvolts; this corresponds to a reading of 150, which was that actually obtained.

The rectifier reading, we have seen, corresponds to a certain amplified voltage independent of the frequency. Let the amplification of a wave of frequency $\omega/(2\pi)$ be $Y(\omega)$, so that an input wave of e volts is amplified to eY volts at the rectifier. Let us take as a basic frequency $\omega_0/(2\pi)$, the frequency of maximum response (in the authors' case 13 000 cycles per sec.), and let the

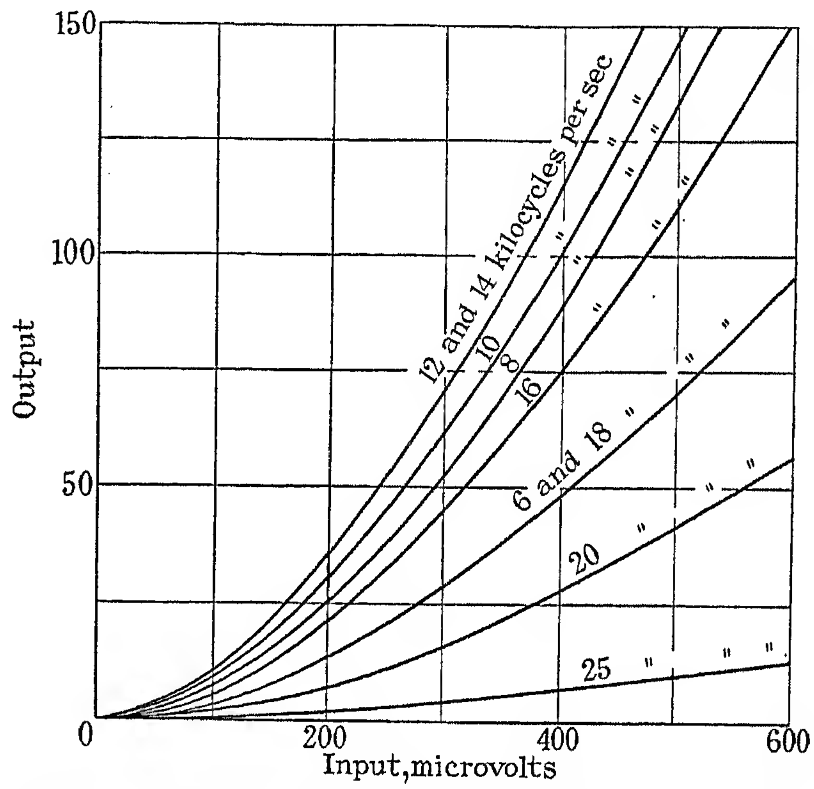

Fig. 25—Calibration curves for transformer, filter, amplifier, and rectifier.

amplification be Y_0. A voltage input e_0 of this frequency will give the same reading as the previous wave, provided $eY = e_0Y_0$; in fact, the reading (d) is given by

$$d=\delta\frac{1}{\sqrt{2}}eY=\delta\frac{1}{\sqrt{2}}e_0Y_0 \quad . \quad . \quad . \quad (12)$$

where δ is an aperiodic constant of the rectifier which, however, varies with the r.m.s. voltage of the applied wave.

Now suppose the discharge current, which has a uniform frequency spectrum, is

$$i=i_0\left[\cos(\omega t-\theta_1)+\cos 3(\omega t-\theta_3)+\cos 5(\omega t-\theta_5)+\dots\right]$$

where $\omega = 2\pi \times 50$.

The aperiodic character of the bridge ensures that the voltage across the filter input transformer is an aperiodic multiple, $1/A$ [see equation (2)]. Thus the voltage across the filter input transformer is $v = i/A$.

The voltage supplied to the rectifier is:—

$$\frac{i_0}{A}[Y_1 \cos(\omega t - \theta_1 - \phi_1) + Y_3 \cos 3(\omega t - \theta_3 - \phi_3) + Y_5 \cos 5(\omega t - \theta_5 - \phi_5) + \ldots]$$

where the ϕ's are phase-shifts and are unimportant.

The r.m.s. voltage of this wave is

$$\frac{i_0}{A\sqrt{2}}\sqrt{(Y_1^2 + Y_3^2 + Y_5^2 + \ldots)}$$
$$= \frac{i_0 Y_0}{A\sqrt{2}}\sqrt{\left[\left(\frac{Y_1}{Y_0}\right)^2 + \left(\frac{Y_3}{Y_0}\right)^2 + \left(\frac{Y_5}{Y_0}\right)^2 + \ldots\right]}$$
$$= \frac{i_0 Y_0}{A\sqrt{2}}\sqrt{\left[\left(\frac{e_0}{e_1}\right)^2 + \left(\frac{e_0}{e_3}\right)^2 + \left(\frac{e_0}{e_5}\right)^2 + \ldots\right]}$$

The expression under the square-root sign is best found as the ratio of the area of the curve representing $(e_0/e)^2$ plotted against frequency, divided by 100, as the frequencies of the waves are 100 cycles per sec. apart. We get, then, that the r.m.s. voltage of the amplified wave is:—

$$\frac{i_0}{A\sqrt{2}}Y_0\sqrt{\left[\left(\frac{e_0}{e_1}\right)^2 + \left(\frac{e_0}{e_3}\right)^2 + \left(\frac{e_0}{e_5}\right)^2 + \ldots\right]} = \frac{i_0 Y_0}{A\sqrt{2}}k$$

k being found from the calibrations and proportional to the square root of the band width accepted by the apparatus. The deflection due to this wave is

$$d = \delta\frac{i_0 Y_0 k}{A\sqrt{2}} \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where δ is the rectifier constant for the correct r.m.s. input. The value of δY_0 is found from equation (12) by looking up the curve corresponding to $\omega_0/(2\pi)$ for the same rectifier reading. This gives the value of e_0 corresponding to the value of d. Equations (12) and (13) give

$$i_0 = e_0 A/k \quad . \quad . \quad . \quad . \quad . \quad (7)$$

For the apparatus whose calibrations are shown in Fig. 25, the value of the square root has been calculated to be 10·5, so that, for this instrument,

$$i_0 = \frac{e_0 A}{10 \cdot 5}$$

[The discussion on this paper will be found on page 88.]

ROUTINE OVER-VOLTAGE TESTING OF HIGH-VOLTAGE CABLES

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SUMMARY

Routine over-voltage testing by direct current at high voltages is considered as a means of locating and eliminating weaknesses in the insulation of high-voltage cables, which might otherwise develop into breakdowns in service. A series of tests carried out on a cable network operating at 11 kV is described, from the results of which conclusions are drawn as to the lines on which tests should be carried out and the extent to which service breakdowns may be eliminated.

INTRODUCTION

Cable breakdowns may be divided into two main classes, those in which a sudden failure takes place—usually as the result of external damage to the cable—and those in which failure follows a comparatively slow deterioration of the insulation caused either by electrical stress or by the ingress of moisture. In the latter class of breakdown the insulation is gradually weakened at a particular spot, and the function of routine over-voltage testing is to detect such spots by completing their breakdown before failure occurs in service.

Two factors are of primary importance in ensuring the detection of incipient breakdowns in this way, namely, the test voltage chosen and the interval of time between one test and the next. The test voltage should be as high as can be applied without undue risk of breaking down healthy cable, and the interval of time should be sufficiently short to prevent a cable, which has withstood one test, breaking down in service before the next is applied.

RESULTS OBTAINED IN PRACTICE

Particulars will now be given of a series of routine over-voltage tests which have been carried out, and the circumstances under which they were undertaken.

Description of Cable Network

The cable network to which these tests were applied consisted of 3-core belted high-voltage cables having dielectric thicknesses of 0·18 in., 0·2 in., 0·24 in., and 0·3 in. between conductors and between conductors and earth, all of which had been purchased for operation at 5·5 kV, except those having a 0·3-in. dielectric. They had been put into commission at various dates from 1906 onwards, and had been operated at 5·5 kV, 25 cycles per sec., until 1931, when a start was made to increase the operating voltage to 11 kV and the frequency to 50 cycles per sec.

It was known at the time when the decision to increase the operating voltage was made that the standardization of dielectric thicknesses of less than 0·3 in. for 11-kV cables was contemplated, although the new standards were not published until 1933, and it was thought that there was a reasonably good prospect of operating the smaller-dielectric-thickness cables satisfactorily at the higher voltage. Subsequent experience has, however, emphasized the fact that the standardization of reduced dielectric thicknesses for 11-kV cables has only been made possible by improved manufacturing technique, and has shown that cables manufactured under the older processes and having dielectric thicknesses of less than 0·3 in. cannot necessarily be safely operated at 11 kV.

Before the operating voltage was increased a d.c. over-voltage test of 20 kV between conductors and 14 kV between conductors and earth was applied on each section of the network. This test was later raised to 30 kV between conductors and 18 kV between conductors and earth, and later still to 50 kV between conductors and between conductors and earth, when routine testing had been adopted.

Table 1

MILES OF SMALL-DIELECTRIC-THICKNESS CABLE IN COMMISSION AT 11 kV

	0·18-in. dielectric thickness	0·2-in. dielectric thickness	0·24-in. dielectric thickness	Total
February, 1932 ..	6	7	42	55
July, 1932 ..	7	11	51	69
December, 1932..	8	20	65	93
June, 1933 ..	—	21	38	59
December, 1933..	—	21	34	55
June, 1934 ..	—	22	31	53
December, 1934..	—	22	29	51
December, 1935..	—	25	20	45

In Table 1 are given the lengths of 0·18-in., 0·2-in., and 0·24-in. dielectric cables in commission at 11 kV at various times during the years 1932, 1933, 1934, and 1935. It will be noticed that the 0·18-in. dielectric cable had been entirely eliminated by June, 1933, and that the length of 0·24-in. dielectric cable in commission at 11 kV after reaching a maximum in December, 1932, was progressively reduced from then on. This reduction in the length of small-dielectric-thickness cable was brought about to some extent by replacement, but mainly by a reorganization of networks whereby cable which had become redundant as a result of the increase in operating voltage from 5·5 to 11 kV was cut out of circuit.

Routine Over-voltage Tests

At the beginning of 1932, breakdowns started to take place on cable having dielectric thicknesses of less than 0·3 in., and, as more cable was changed over to 11 kV, it became apparent that the number of breakdowns was becoming greater than could be tolerated and that unless some means could be found of clearing the faults before breakdown occurred the whole of the small-dielectric-thickness cable would have to be replaced. Routine over-voltage testing was therefore resorted to, and a start was made with a.c. over-voltage testing at 16·5 kV, i.e. 1½ times working voltage. The results were disappointing. Although a few weak spots were located, service breakdowns still continued without any noticeable diminution in frequency. In some cases such breakdowns occurred very shortly after testing.

It was thought that a higher test voltage might be more effective and, in view of the excessive size of the testing transformers required for higher a.c. voltages, it was decided to adopt d.c. testing. It was also felt that any considerable increase in the a.c. testing voltage might have a harmful effect on the insulation of the cable, whereas a high d.c. voltage would not cause any damage unless breakdown actually occurred.

The possibility of using time/current curves to detect incipient failures was also considered. (The application of this method to high-voltage cables, and the results obtained, have been described by H. S. Phelps and E. D. Tanzer.*) This method, however, seemed too uncertain and too cumbersome to be applied to a network composed of a large number of sections of cable. High-voltage d.c. testing, which appeared to be a more positive and direct method, was therefore adopted. The charging current should, however, be carefully observed when a high-voltage d.c. test is applied to a cable. This matter will be dealt with in more detail under the heading " Test Procedure " (see page 86).

Test Voltage Adopted

Before high-voltage d.c. tests were initiated the following two experiments were carried out to determine a suitable test voltage.

Experiment (1).

A length of 3 500 yards of 3-core 0·15-sq. in. cable, having a dielectric thickness of 0·24 in., was tested for ultimate breakdown. This cable had been in commission at 5·5 kV since 1906, but had not been operated at all at 11 kV. A voltage of 120 kV between conductors and 60 kV between conductors and earth was reached on all cores without breakdown of the cable, although one or two joint failures occurred. On raising the voltage further, breakdown to earth took place at slightly over 60 kV. Examination of the fault, when located, showed that the belt insulation was rather badly wrinkled at the point of breakdown. The puncture was clean and there was little doubt that no deterioration of the insulation, other than wrinkling of the paper and general drying-out of the compound, had taken place before the test.

* " A New Method for the Routine Testing of Alternating-Current High-Voltage Paper-Insulated Cables," *Transactions of the American I.E.E.*, 1923, vol. 42, p. 54.

Experiment (2).

A number of short sample lengths of cable taken from various parts of the network and manufactured at various dates between 1906 and 1927 were tested for breakdown. The lowest breakdown stress on these samples was 560 volts (d.c.) per mil, corresponding to an actual test voltage of 100 800 volts on a cable having a dielectric thickness of 0·18 in.

Taking the results of these two experiments into account, it was decided to adopt a voltage of 50 kV between conductors and between conductors and earth. It was recognized that the application of such a high voltage between conductors and earth would probably produce a considerable number of joint failures, particularly in the case of joints designed for 5·5-kV operation. This proved to be the case, but it was noticeable that the weaker joints having been eliminated and a voltage of 50 kV having been reached on one test, very few breakdowns occurred on joints in the course of subsequent tests.

An analysis of these joint failures is given in Table 2. It throws some light on the choice of a suitable test voltage. The great majority of breakdowns on joints occurred between conductor and earth. The total number of joints tested was approximately 1 100, and approximately 7 per cent broke down. Approximately 60 per cent of the joint breakdowns occurred at over 40 kV. Had a maximum voltage of, say, 35 kV between conductors and earth been adopted instead of 50 kV, considerable trouble and expense would have been avoided, and it is probable that this voltage would have been adequate as a test for the cable.

Table 2

ANALYSIS OF JOINT-BOX BREAKDOWNS ON TEST

Test voltage at which breakdown occurred	Number of breakdowns in first series of tests	Number of breakdowns in subsequent tests
Up to 10 kV	3	0
11 to 20 kV	5	0
21 to 30 kV	12	0
31 to 40 kV	8	2
41 to 50 kV	35	8
Total ..	63	10

Experience indicates that suitable d.c. voltages for the testing of cables having dielectric thicknesses of between 0·18 in. and 0·24 in. are 50 kV between conductors and 35 kV between conductors and earth.

Interval Between Tests

The interval of time which may safely be allowed to elapse between one test and the next depends upon the test voltage adopted and upon the speed at which deterioration of the insulation takes place in service. Deterioration by electrical stress may originate at the conductor, gradually penetrating the dielectric from within; or it may originate at an intermediate point between two conductors or between a conductor and

Table 3

CABLE BREAKDOWNS IN SERVICE

Reference No.	Dielectric thickness of cable	Date of laying	Date of increase in voltage to 11 kV	Particulars of last test				Date of breakdown
				D.C. voltage	Date	A.C. voltage	Date	
	in.			kV		kV		
1	0·24	1911	Dec., 1931	20/14	8.12.31	—	—	1. 2.32
2	0·18	1924	Dec., 1931	20/14	22. 3.32	—	—	14. 2.32
3	0·24	1914	Nov., 1931	20/14	18. 7.31	—	—	3. 5.32
4	0·18	1925	Aug., 1931	20/14	11. 7.31	—	—	23. 7.32
5	0·24	1920	Dec., 1931	20/14	28. 7.31	—	—	25. 9.32
6	0·24	1911	Dec., 1931	30/18	16. 8.32	—	—	3.10.32
7	0·24	1914	Nov., 1931	20/14	31. 7.31	16·5	28. 8.32	13.10.32
8	0·24	1920	Dec., 1931	—	—	16·5	27. 9.32	27.10.32
9	0.24	1912	Nov., 1931	20/14	13.10.31	16·5	16.10.32	9.11.32
10	0·18	1925	Aug., 1931	30/25	13. 8.32	16·5	18.10.32	27.11.32
11	0·24	1920	Dec., 1931	—	—	16·5	24.11.32	24.11.32
12	0·24	1924	Oct., 1931	20/14	3. 9.31	16·5	14. 9.32	18.12.32
13	0·24	1912	Aug., 1931	20/14	4. 7.31	16·5	30.10.32	20. 1.33
14	0·24	1920	Jan., 1932	—	—	16·5	11. 9.32	26. 1.33
15	0·24	1911	Aug., 1932	30/18	11. 3.32	—	—	9. 3.33
16	0·24	1915	July, 1932	40/30	12.11.32	—	—	8. 7.33
17	0·24	1915	April, 1932	30/30	4.10.33	—	—	24.12.33
18	0·2	1918	June, 1931	50/50	30. 4.33	—	—	10. 1.34
19	0·24	1912	Aug., 1931	50/50	5. 1.34	—	—	13. 2.34
20	0·24	1921	Sept., 1932	50/50	7. 2.34	—	—	25.11.34
21	0.24	1921	Sept., 1932	50/35	9. 2.35	—	—	1. 4.35
22	0·2	1921	Dec., 1932	50/35	26. 6.35	—	—	8.12.35

earth; for instance, at the surface of the core insulation, or in the packing between the cores on a 3-core belted cable. Or again it may be that some action takes place which gradually reduces the value of the insulation more or less evenly throughout its thickness. Ingress of moisture causes a reduction in the effective thickness of the insulation as it penetrates from without. Whatever the actual process may be, there arrives a stage in its development at which the insulation has become sufficiently weak to be punctured by the voltage adopted for routine testing. If allowed to develop further, deterioration will reach the stage at which the insulation has become sufficiently weak to be broken down by the working voltage of the cable. The interval between one test and the next should be less than the minimum time required for this further development to take place.

The speed of deterioration of cable in service is not known, but consideration of the service breakdowns which occurred on the network described above, both before and after routine over-voltage testing was adopted, affords a basis for assessing a suitable maximum interval between tests. Table 3 gives particulars of service breakdowns, including the class of cable concerned, its length of service, and the interval which had elapsed between the last d.c. over-voltage test (if any) and the occurrence of the breakdown. In the case of the five breakdowns which occurred subsequent to the application of an over-voltage test of 50 kV (Nos. 18, 19, 20, 21, and 22), the intervals between test and breakdown were 9 months, 6 weeks, 9 months, 7 weeks, and 5½ months respectively.

For the cable network dealt with in this paper it has been decided to aim at allowing an interval of not more than 6 months to elapse between one test and the next.

Effectiveness of Routine Over-voltage Testing

The effectiveness of routine d.c. over-voltage testing in reducing service breakdowns can be judged by a comparison of the number of service breakdowns which took place before and after testing, taking into account the length of cable in commission (Table 4), and by the

Table 4

ANALYSIS OF SERVICE BREAKDOWNS

Period	Average length of cable in commission (miles)	Number of breakdowns	
		Before testing at 50 kV (d.c.) or more than 6 months after previous test at 50 kV (d.c.)	Within 6 months after previous test at 50 kV (d.c.)
Aug. to Dec., 1931 ..	30	0	0
1932	80	12	0
1933	70	5	0
1934	50	2	1
1935	45	0	2
Total ..	55	19	3

Table 5

Cable Breakdowns Under Test

Reference No.	Dielectric thickness of cable	Date of laying	Date of increase in voltage to 11 kV	Particulars of last test		Voltage at which breakdown occurred	Date of breakdown
				Voltage (d.c.)	Date		
				kV		kV	
1	0·18	1924	Dec., 1931	20/14	22. 3.32	38, after 10 min.	18.10.32
2	0·24	1913	Aug., 1932	20/14	21.10.31	48	7.12.32
3	0·24	1924	Aug., 1931	20/14	3. 9.31	16	20.12.32
4	0·24	1914	Dec., 1931	50/50	29.11.32	48	28. 2.33
5	0·24	1919	Dec., 1931	20/14	12.10.31	46	8. 3.33
6	0·24	1913	Dec., 1931	50/50	9.12.32	50, after 8 min.	21. 3.33
7	0·24	1908	Jan., 1933	22/16	9. 3.32	48	21. 3.33
8	0·24	1924	Oct., 1931	No record		22	4. 4.33
9	0·24	1924	Oct., 1931	No record		40	6. 4.33
10	0·24	1921	Dec., 1932	No record		No record	30. 6.33
11	0·24	1913	April, 1933	50/50	20. 1.33	No record	9. 7.33
12	0·24	1924	Sept., 1932	30/18	16. 8.32	50, after 5 min.	8. 5.33
13	0·24	1918	July, 1932	30/18	13. 7.33	50, after 3 min.	1.10.33
14	0·24	1915	Jan., 1932	30/30	19. 6.33	48	5.10.33
15	0·24	1912	Oct., 1931	30/18	22. 4.33	40	30.10.33
16	0·24	1912	Aug., 1931	50/50	3.11.33	46	12.11.33
17	0·24	1912	Dec., 1931	50/50	3.11.33	48	12.11.33
18	0·24	1915	Aug., 1931	50/50	8.10.33	44	31.11.33
19	0.24	1915	Oct., 1933	No record		50, after 4 min.	9.12.33
20	0·24	1912	Dec., 1931	50/50	13.12.33	38	9. 1.34
21	0·24	1919	April, 1932	30/30	30.12.33	50	17. 1.34
22	0·24	1912	Feb., 1934	No record		10	18. 2.34
23	0·24	1912	Feb., 1934	No record		50	20. 2.34
24	0·24	1919	Aug., 1932	50/50	1.12.33	40	24. 3.34
25	0·24	1914	Aug., 1931	50/50	3.12.33	40	16. 4.34
26	0·24	1922	Sept., 1933	No record		32	17. 7.34
27	0·24	1919	Oct., 1931	50/50	10.11.33	34	25. 9.34
28	0·24	1921	Sept., 1932	50/50	7. 2.34	50, after 1 min.	28.11.34
29	0·2	1921	Dec., 1932	50/50	30.10.34	40	30.11.34

number of breakdowns occurring in the course of testing (Tables 5 and 6).

It will be noticed that three breakdowns occurred in service within 6 months of a d.c. test at 50 kV. As one of these (No. 19) was accompanied by a severe flashover on the switchgear controlling the cable there is reason to suppose that it may have been caused by a surge, either set up by the flashover on the switchgear or causing this flashover as well as breakdown on the cable.

Table 6

Analysis of Cable Breakdowns on Test

Period	Average length of cable in commission (miles)	Number of breakdowns	
		Before testing at 50 kV (d.c.)	After testing at 50 kV
Oct., 1932, to Dec., 1933	70	13	6
1934	50	4	6
1935	45	2	4
Total ..	57	19	16

Breakdown on Test

Table 5 gives a list of breakdowns on test, with particulars of the cable concerned similar to those given in Table 4. Table 6 gives an analysis of breakdowns on test in relation to the length of cable in commission, and shows in how many cases the cable had been previously routine-tested. It will be seen from Tables 5 and 6 that breakdowns on test continued to occur after the cables had been subjected to previous tests. It may be concluded, therefore, that deterioration was taking place, reducing the breakdown value of the insulation, and that, if this deterioration had been allowed to continue unchecked, breakdowns in service would have followed.

Duration of Test

The duration of test on the first series of tests carried out was 15 minutes. It was subsequently reduced to 5 minutes, and later to 1 minute. It will be noticed from Table 5 that in a few cases breakdown occurred after the voltage had been maintained at its full value

for an appreciable time. This can be explained by supposing that a slight increase took place in the voltage applied during the application of the test, or by assuming that some gradual weakening of the insulation occurred under test before breakdown took place. The first supposition would be reasonable in an isolated case, but this effect has been noticed sufficiently often to indicate that gradual breakdown can be effected under certain circumstances by the application of a steady d.c. voltage. The dielectric of most of the cables tested was by no means perfect according to modern standards, and it seems probable that ionization of occluded gases in the spaces between papers resulted in a reduction of the electric strength of the insulation under sustained d.c. over-voltage. Although this effect is not thought to be harmful to the cable, there is nothing to be gained by inducing breakdown in this way, and it seems advisable, therefore, to limit the duration of the test to a short period.

TEST PROCEDURE

Various methods of testing can be used, but the procedure which can be recommended is to bunch all conductors together and apply voltage between conductors and earth, the conductor being given a negative potential. If the cable withstands this test, voltage should be applied between conductors, i.e. between red and white, between red and blue, and between white and blue. By this method the exact nature of a breakdown, if it takes place, can be readily established. The voltage should be raised fairly slowly, about 1 minute being normally taken to reach 50 kV.

When voltage is first applied there is a momentary kick of charging current. As the voltage is raised the charging current fluctuates according to the rate and regularity of the rise in voltage. When a steady voltage has been reached the charging current normally falls to a steady value. Breakdowns on test usually take place before the voltage has attained its full value and consequently before the charging current has fallen to a steady value. They do, however, sometimes occur after the full voltage has been reached and in such cases they may be heralded by a more or less gradual increase in the charging current. Any such increase in the charging current after the voltage has reached a steady value should strictly be described as a leakage current, and must be regarded as a sign that there may be a defect in the cable. When there is any such indication of leakage the voltage should be maintained until definite breakdown occurs or steady conditions are regained. Fluctuations in charging current are not, however, always due to cable defects. They are sometimes caused by leakage at the ends of the cable under test, or on the testing gear itself.

Certain types of 11-kV switchgear will withstand test voltages of the values used in the series of tests described; for instance, cubicle-type gear in which conductors are mounted on adequate porcelain bushings and insulators which are clean and dry at the time of the test. Compound-filled switchgear, however, in which varnished paper-board tube insulation is used, is somewhat susceptible to breakdown at high d.c. voltages and it is advisable to disconnect cables from this type of gear before making the test. Cables must, of course, also be disconnected from transformers before a test, and it is advisable to install isolating links for this purpose if cables directly connected to transformers have to be routine-tested.

If a cable can only be released from service for a comparatively short time it is advisable to adopt step testing, in which a complete round of tests between conductor and earth and between conductors is carried out at, say, 20 kV, 30 kV, 40 kV, and 50 kV. Then if a breakdown occurs at, say, 45 kV, repairs can be carried out and the cable put back into commission with the knowledge that it has, at any rate, had a complete test at 40 kV.

COST OF TESTING

On the network described above, which consists of approximately 50 miles of low-dielectric-thickness cable split up into 80 sections, about 180 tests per annum are necessary to ensure that each section is tested at intervals not exceeding 6 months. It has been found that an engineer, with driver, jointer, and mate, can carry out approximately 350 tests per annum if their time is wholly devoted to the work.

The cost of testing the small-dielectric-thickness cables has been found to amount to approximately £1 500 per annum, including salaries, wages, renewals to testing apparatus, and repairs to cable broken down on test. This represents the cost of keeping about 50 miles of cable in commission. The cost of replacing this cable may be estimated at not less than £100 000, and, even if no account is taken of the inconvenience which would be caused by the replacement of such a considerable mileage of cable, the annual cost of testing is amply justified by the saving of capital charges effected.

RESULTS OBTAINED ON OTHER NETWORKS

The case for routine over-voltage d.c. testing, put forward in this paper, rests mainly on the results described above, which were obtained on a network of cables operating at a higher voltage than that for which they were designed. The field in which over-voltage d.c. testing may be applied is not, however, confined to such networks, and particulars are given in the Appendix of a few typical cases of faults which have been detected on 33-kV and 11-kV cables operating at the voltages for which they were designed.

Routine over-voltage d.c. testing has also been used in the United States, and the results which have been published show that some success has been obtained in that country in clearing faults.* The voltages generally used do not, however, seem to have been sufficiently high in relation to working voltages to give effective immunity from service breakdowns.

CONCLUSIONS

It is apparent from the results obtained in the series of tests described above that systematic routine d.c. over-voltage testing will eliminate a large proportion of service breakdowns arising from deterioration of cable insulation. The over-voltage applied must, however,

* *Proceedings of the National Electric Light Association*, 1927, vol. 84, p. 1428; 1928, vol. 85, p. 1548; 1930, vol. 87, p. 117; also C. L. Kasson: "High-voltage Field Testing of Cables," *Electrical World*, 1926, vol. 88, p. 1117.

be considerable, if a reasonable period of immunity from breakdown is to be ensured. Approximately 5 times the a.c. working voltage may be suggested as a suitable value.

It is clear that the application of high d.c. voltages is not harmful to sound cable, although a certain number of joints which would probably continue to operate satisfactorily at the ordinary working voltage must be expected to break down on test.

It may therefore be concluded that routine d.c. over-voltage testing may be the means of extending considerably the useful life of cable which would otherwise have to be replaced, and that by its use a considerable proportion of service breakdowns, with the dislocation of supplies attendant thereon, may be avoided.

Acknowledgments

The author wishes to express his indebtedness to Mr. F. Forrest for helpful criticism of the paper, and to Dr. D. M. Robinson and Mr. F. S. Smith for information which they have given and suggestions which they have made.

He is also indebted to Mr. H. J. Cox and other colleagues who have assisted him in the recording and classification of test results.

APPENDIX

Miscellaneous Faults Detected by Direct-Current Over-voltage Testing

Item 1.

On the 28th February, 1935, an 11-kV 0·06-sq. in. 3-core belted cable broke down between one phase conductor and earth at 23 kV (d.c.). The fault was located at a position where a sewer manhole shaft had recently been constructed. The cable had been damaged at several points over a distance of about 2 yards by a pick or some other instrument, and moisture was found in the insulation. The damage had no doubt been caused when the sewer works were carried out.

Item 2.

On the 1st September, 1934, a 33-kV 0·2-sq. in. 3-core belted cable broke down between two phases at 70 kV (d.c.). This cable was laid on racks in a cable chase in a generating station. The fault had developed at a point where the cable turned a corner about 18 in. off the bend. A pronounced bulge had been formed in the lead sheath, which had increased in diameter by about $\frac{3}{4}$ in. The belt papers were burst in a longitudinal crack about 18 in. long. The outer-core papers were also burst in longitudinal cracks about 12 in. long on all cores, the damage narrowing down to a small hole about $\frac{1}{8}$ in. diameter at the strand. The origin of the breakdown on the blue strand was situated 10 in. along the cable, measured from the origin of the breakdown on the red strand, and the origin of the breakdown on the white strand was a further 8 in. along the cable. The crack in the belt, the interstices between the cores, and the cracks in the core insulation, were full of heavily carbonized oil. It was thought that the fault had been caused primarily by mechanical stress on the insulation near the bend of the cable due to movement of the cores on loading and unloading, followed by electric discharge and consequent generation of high gas pressure. In view of the conditions revealed, it was surprising that the cable had not broken down in service.

Item 3.

On the 19th May, 1935, a 33-kV 0·25-sq. in. 3-core triple-lead-sheath cable broke down after the test voltage had been brought up slowly and maintained at 60 kV (d.c.) for 1 minute. A small hole about $\frac{1}{32}$ in. diameter was found in the lead sheath, and moisture was detected in the dielectric, reaching right through to the strand. Black compound, also, from the hessian serving had penetrated 50 of the 66 papers forming the dielectric. There was no sign of damage to the serving and armour. It was concluded that the breakdown was due to the ingress of moisture through a flaw in the lead sheath. The moisture had taken a long time to penetrate, the cable having been in service for 6 years.

Item 4.

On the 3rd June, 1935, a 33-kV 0·2-sq. in. 3-core belted cable broke down between two phases at 50 kV (d.c.). The path of the fault started on the outside of the two conductors, penetrated the core insulation to the last 10 papers or so of the core insulation, and then tracked round under the belt. Small pin-hole burns through 10 to 20 papers were noticed around the main fault track on both cores. These holes were more frequent and more pronounced near the copper. Tree burns—characteristic of excess electric stress—were also noticed near the fault: they disappeared at about the 25th paper, counting from the outside. There was no sign of treeing at a distance of more than 15 in. on each side of the fault. The cable was in very good condition except in the immediate neighbourhood of the fault. The presence of the pin-hole burns at the fault suggests that the dielectric had been damaged by a surge at a point where some local deterioration had taken place. Possibly the deterioration had followed damage by a surge.

Item 5.

On the 8th November, 1935, a 33-kV 0·25-sq. in. 3-core triple-lead-sheath cable broke down at 35 kV (d.c.). The fault was located at a joint. The insulation over the ferrule consisted of a laminated paper tube. This tube had split from its centre to one end and had opened out, leaving a crack about $\frac{1}{8}$ in. across at its widest point. The edges of the paper laminations were charred at this crack, particularly near the ferrule, at which electrical breakdown had no doubt originated. A breakdown in service which had previously occurred on a joint of the same type, exhibited almost exactly similar features. In this case, however, the fault had completed its path along the surface of the core insulation to the bell-mouth on the lead sheath.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 15TH JANUARY, 1936, ON THE PAPERS BY MESSRS. ARMAN AND STARR (SEE PAGE 67) AND MR. KIBBLE-WHITE (SEE PAGE 82).

Dr. E. H. Rayner: Since the days when I first had to handle electric generating plant, the usual size of prime generators has increased a hundredfold, thanks to the development of the turbine. This increase could not have been achieved on a commercial scale, nor could the large amounts of power generated in one building have been distributed economically throughout the area of consumption, if there had not been a corresponding twentyfold increase in the voltage that can be transmitted underground.

The combination of economic conditions and engineering possibilities in other electrical and mechanical branches of engineering has been an inducement to the cable industry to develop cables for higher voltages, and this development has been accelerated in the last few years. The high-voltage cable is the philosophical basis of our present sizes of generating units and generating stations; without it, the 100 000-kW or 200 000-kW station would not be an economic possibility.

The good qualities of cables are largely taken for granted, and greater attention is not unnaturally given to the measurement of cable characteristics and the detection of possible defects. Efficient methods of detection will no doubt stimulate the underground distribution of electrical power. The importance of this question of the measurement of the properties of cables was brought to my notice a few years ago in discussion with the chief engineer of one of the largest cable manufacturing concerns in Europe, who told me that he saw appreciably less difficulty in developing a 200-kV cable from knowledge of the performance of a 100-kV cable obtained with the methods of measurement now possible than he had found some years before in developing a 30-kV cable from a 15-kV cable.

Referring to the paper by Mr. Arman and Dr. Starr, in Fig. 3 there is shown a delightfully simple arrangement for determining qualitatively the source of the high-frequency components in discharges, by putting a condenser in parallel with the load. More might have been made of the balanced-transformer method perhaps, if the authors had loaded both the transformers with similar loads. Apparently they connected a load to only one of them, and therefore upset the characteristics of the transformers, which vary with the load. It would possibly have been better if they could also have used air-core transformers; the latter may not have been practicable, however, because no transformer with a metal core of the type that they used would have given similar characteristics at different voltages.

In Fig. 5, the condenser C_2 is described as a standard air condenser. The authors mean, I take it, a standard high-voltage condenser, of possibly several hundred kV. Is it in fact a compressed-gas condenser?

The authors seem to favour a frequency range from 11 000 to 21 000 cycles, but there does not seem to me to have been any particular reason for this choice. It would be of interest to learn what may be expected below and above this range.

Figs. 15 to 22 are very interesting and suggestive, and it will be interesting to hear the experience of other investigators on this subject, including their views on the effect of stranding.

Turning to the paper by Mr. Kibblewhite, I suppose that the cables mentioned by the author were not supplied originally with the idea that their voltage would perhaps be doubled in 20 years' time. To stand double voltage under commercial conditions is a very notable performance.

In Table 3 it is not quite clear what the headings to some of the columns mean. Under "D.C. voltage," for instance, the author gives two ratings, 20 kV and 14 kV; are these the voltages between cores and from core to earth respectively? Does the heading "A.C. voltage" refer to the voltage between cores or to earth?

There is one point in connection with the test procedure which seems to me to be of interest. I should like to know whether a cable can be damaged by too rapid a discharge after the application of a high d.c. over-voltage for some time. The voltage gradient in a cable under d.c. conditions is not necessarily of the same shape, if the cable is a little defective, as under a.c. conditions. In the latter case the voltage gradient depends on capacitance considerations, whereas the application of direct current for some time may give rise to a distribution which will depend entirely on resistance effects, and the mixing-up of those two conditions under sudden discharge may have some effect.

Mr. T. R. Scott: Mr. Arman and Dr. Starr present an admirable exposition of the circuit and apparatus theory relating to discharge bridges, but fail to some extent to build up a case for the use of such bridges. They might have indicated that in the case of certain dielectrics quite considerable variations of power factor with voltage are possible without any ionization or discharge being present. The use of the discharge bridge in analysing such dielectric characteristics in conjunction with the usual Schering-bridge arrangement will undoubtedly be of great importance in fundamental dielectric research. The paper is, however, in spite of its broad title, concerned primarily with impregnated paper cables, and it is suggested by the authors that the bridge will show up discharges likely to prove serious in service. It is undoubtedly true that discharges occurring in voids of dimensions such that the lack of impregnation can be detected visually will be indicated by the bridge. It is by no means certain that ionization in a more or less isolated void of small dimensions at some distance along the cable, so that the circuit impedance is high, will be shown up. Yet such voids may be dangerous. Some data on the sensitivity of the bridge and the effect of impedance due to length of cable would add to the value of the paper.

Mr. Kibblewhite's network was of an experimental nature, and although he has proved the economic value of his own tests it does not follow that such tests are useful or economic on modern 11-kV networks. At higher voltages, however, with higher working stresses applied to the insulation it is possible that some gain

may be achieved by introducing such routine tests. The author has also proved that there is a good case for applying periodic high-tension d.c. tests from the point of view of detecting incipient faults due to accidents or external influences.

One has some reluctance, however, in following Mr. Kibblewhite so far as his suggestion that 5 times working voltage is necessary in this high-tension test. According to the examples given in the Appendix to the paper all the miscellaneous faults detected were picked out by voltages less than 4 times working voltage. It is questionable whether we have so far explored all the complexities of dielectric phenomena under high stresses to such an extent that we can afford to run risks by elevating the test voltage unduly. It is more probable that development will render tests more sensitive, so that faults can be detected at lower voltages, and the use of higher voltage to burn out the fault will be reserved until the decision is taken that the occasion is suitable for clearing the incipient fault.

In conclusion, I note that there is no discussion in Mr. Kibblewhite's paper of the effect of the temperature of the cable on the test results. On general grounds one would expect temperature to have quite a considerable effect on the behaviour of the dielectric under d.c. stress. There are diverse opinions on the nature and magnitude of this effect, and it would be of interest to have the author's opinions or experience in regard to it.

Mr. J. Nethersole: My remarks will be confined to Mr. Kibblewhite's paper.

In his Conclusions the author states "It is clear that the application of high d.c. voltages is not harmful to sound cable. . . ." I have noticed that there is a divergence of opinion on this matter in the cable manufacturing industry. Certain manufacturers seem to be doubtful whether or not the application of a high d.c. voltage will harm a sound cable. The author suggests that for this over-voltage routine testing the d.c. voltage should be 5 times the a.c. working voltage, and the time of application 1 minute. Difficulty may be experienced when applying such a test to 33-kV and 66-kV cables, owing to the terminations not being suitable for the application of such a voltage. The author states that when testing cables connected to compound-filled switchgear it is advisable to disconnect the cables before making the test. The necessity for doing this will add very considerably to the cost of testing. Would it not be better to apply a lower voltage than 5 times the normal voltage, for a longer period of time, and avoid disconnecting from switchgear?

With reference to the time of test, in commenting on Table 5 the author points out that in several cases breakdown occurred after the d.c. voltage had been applied for 5 minutes or even longer, and the suggestion is made that breakdown was due to ionization of occluded gases. That suggestion is not supported by Dr. Robinson's paper,* which states that breakdown is due purely to alternating current, and is not affected by direct current, where occluded gases are concerned. Dr. Robinson also states that this very fact is useful for the application of high-voltage d.c. testing to cables, but I suggest that the time of application should probably be considerably longer than 1 minute.

Mr. Kibblewhite indicates that high-voltage d.c. testing can be advantageous in determining where deterioration of a cable is taking place. He is applying this test to cable which is working at a higher voltage than that for which it was designed; he expects deterioration, and tries to eliminate it before there is a breakdown in service.

I should like to ask the author his opinion on a different aspect of the application of routine d.c. testing. In connection with modern high-voltage cable, cases arise where factory tests do not show up faulty lengths; moisture may get in via small holes in the lead sheaths and damage the insulation, and bad impregnation sometimes occurs. Would it not be possible, if an agreed test voltage and length of time could be fixed among manufacturers, to utilize high-voltage d.c. testing for a maintenance guarantee test after, say, 2 years' service?

Dr. P. Dunsheath: The subject matter of the papers appeals to me from the standpoint of what is going on in a dielectric subjected either to the d.c. test which Mr. Kibblewhite applies or to the discharge tests of the other two authors. Mr. Kibblewhite shows quite early in his paper that although he can anticipate failure on his system by applying a d.c. over-voltage and so weed out weak lengths, an a.c. over-voltage of 50 per cent is useless for the purpose. By applying an alternating over-voltage he actually makes things worse, by introducing into the system the weaknesses which the test is intended to eliminate. The question therefore arises, what is there in the d.c. test which enables us to find out the weak spots and eliminate them without making other weak spots? It is clear that the application of the d.c. test after a.c. operation introduces entirely new physical conditions in the dielectric; and I am disappointed that the author does not offer a theory to explain what is going on in the dielectric under these conditions.

Why is it that with direct current we can break down the cable without harming it, whereas with alternating current this is impossible? Presumably the cables which Mr. Kibblewhite has been testing have failed by partial deterioration in ordinary work under alternating stress, and the subsequent application of direct current has broken down the remaining good dielectric, either by movement of compound under the applied steady stress, by movement of moisture, or by some other mechanism. We can find a possible answer to the question in the paper by Mr. Arman and Dr. Starr. Fig. 22 in that paper shows that, with alternating current, discharge takes place at about 5 kV; while with direct current, discharge does not take place until much higher voltages are reached—30 kV with the conductor negative and 50 kV with the conductor positive. (I should like to interpose here that I do not remember any statement in Mr. Kibblewhite's paper as to whether the conductor was positive or negative; in view of this result recorded in the joint paper, the question assumes importance.) The point that I wish to make, however, concerns the difference in shape between the a.c. curve and the two d.c. curves. It is quite clear that when direct current is

* *Journal I.E.E.*, 1935, vol. 77, p. 90.

applied the action is very much more delayed than in the case of the a.c. test, where discharge takes place at once. It may be that we have here a complete explanation of the fact that we can sort out cables without deterioration by the use of d.c. tests.

Some years ago I read a paper* giving the results of a number of analyses of dielectric-loss/voltage curves, and I tried to classify the losses into two categories—gaseous and non-gaseous ionization. I am therefore very interested to see in the paper by Mr. Arman and Dr. Starr, curves produced by an entirely different method which are almost identical with my own; for instance the curves in Fig. 16. The connection between the two ideas would repay further investigation.

Mr. S. R. Siviour: As regards the paper by Mr. Arman and Dr. Starr, I am particularly interested in their reference to a sensitive test for moisture, which leads me to hope that they will devise in the future a practical means of field testing for moisture along with other routine testing.

Mr. Kibblewhite's paper is a particularly interesting record of routine testing, as, apart from the cost and difficulty of repairing faults when they occur in service, the question of disturbance to consumers and to the system generally is becoming much more important nowadays. In view of the varied nature of the materials used in cable manufacture, and their lack of affinity to one another, it is remarkable that we do not have more trouble, leaving out of account the nature of the handling which cables receive in course of laying.

The author's experiment to determine the suitable voltage to use for these tests is very interesting; we are all very concerned as to whether the imposition of this d.c. test does any harm to the cable. We have to consider the results of the author's experiment in conjunction with the facts given in the paper by Dr. Robinson† last year, and particularly the test in which he superimposed a d.c. voltage on the a.c. peak voltage, with entirely negative results. Remembering this, and also that with direct current there are no losses other than the conduction losses, that the time element does not appear to come into the question at all, and further that the discharge at voids with direct current takes place only when the cable is charged and discharged, whereas with a.c. 50-cycle supply it occurs 100 times per second; surely we ought in consequence to find some relief from our fears as to the effect of the application of the high-voltage d.c. test.

On the system with which I am connected, 22 such tests have been carried out during the past 12 months on the 11-kV mains, consisting mostly of cable and overhead lines in series. The average length of the cable sections tested varied from 0·5 to 3·5 miles, and a test voltage of 50 kV between phases and 35 kV to earth was used. Of the 22 tests, in 18 cases the cable withstood the applied voltage, but in 2 of these cases faults subsequently occurred. In 2 cases the section failed on test; one of these has given no further trouble, and the other has since failed twice. In the remaining 2 tests the fault occurred on an insulator at the junction of the overhead line with the cable.

* *Journal I.E.E.*, 1933, vol. 73, p. 321.
† *Ibid.*, 1935, vol. 77, p. 97.

We find d.c. testing advantageous for fault location on all classes of high-voltage mains, and in my opinion, and subject to the use of suitable voltages, it does no harm to the cable. The evidence for this assertion is to be found in the "tracking" type of failure, where the a.c. discharge goes on for a considerable time and there is a fairly large area of burned paper: the direct current passes through the remaining wall of otherwise good dielectric with (usually) a clean pinhole. We obtained very similar results to those described by the author, in that shortly after a routine test another failure occurred in service. I attribute this to the fact that during the prior test the remaining sound wall of dielectric had been good enough to withstand the test voltage, but that subsequently the rate of deterioration under a.c. service had increased and the failure shortly afterwards was due to rapid a.c. deterioration in the last stages: dissection of faulty lengths usually reveals this feature.

I agree with the author in advocating the routine testing of old cables and endeavouring to avoid breakdowns in service; but on systems covering extensive areas where ring mains chiefly obtain, there may be difficulties in regularly taking out of commission important sections when one has to visualize the possibility of repairs taking 6 hours or more.

Mr. R. C. Mildner: With regard to the paper by Mr. Arman and Dr. Starr, it is interesting to read the doubts continually expressed in this paper by the authors, and elsewhere by their colleagues, as to the nature of the ionization that is occurring in a cable at the lower stresses; for I presume that they do not intend to deny that the power-factor variation at lower stresses is really an ionization, so much as to doubt whether its origin is gaseous or electrolytic. It is an undoubted fact that moisture in a fibrous material can contribute to the conduction in that material in the manner illustrated by the samples mentioned by the author; but, with the degree of drying which the power factor of their samples indicates, I think it is very unlikely that it is moisture which is causing the power-factor variation.

In any work of a semi-fundamental nature such as this, it is important that the test should include samples of the very highest quality available, and Fig. A shows some test figures obtained on a length of 66-kV cable of standard design which was tested recently. The characteristic is perfectly flat up to a voltage of just over 100 kV; beyond that there is a very slight, but appreciable, rise in power factor. It would be very interesting to have discharge figures for cables of this quality. Cables of similar design to this, and subjected to the same degree of drying, but impregnated under less rigorous conditions, show changes in power factor at the lower stresses similar to those of the samples quoted by the authors; and I suggest that this indicates that it is gaseous ionization and not moisture which causes these effects. These remarks apply equally to cable impregnated with mineral oil or with resin compound.

The authors' results suggest, and our own experience confirms, that there is a difference in the nature of the ionization which can occur at different stresses. In my opinion, this difference is due rather to a difference in the location of the ionization; it may be that the ioniza-

tion which occurs at the lower voltages is highly localized so that its very location prevents it from contributing to the discharges which can be measured by the bridges developed by the authors.

I have one observation to make on Mr. Kibblewhite's paper, namely that it seems to me that the fundamental reason for the flatness of the d.c. breakdown-voltage/time curve is the inherent difficulty with which energy can be fed from the neighbouring insulation into the point of intrinsic weakness which is to constitute the fault. That, I suggest, is the real reason for the valuable characteristics of d.c. testing.

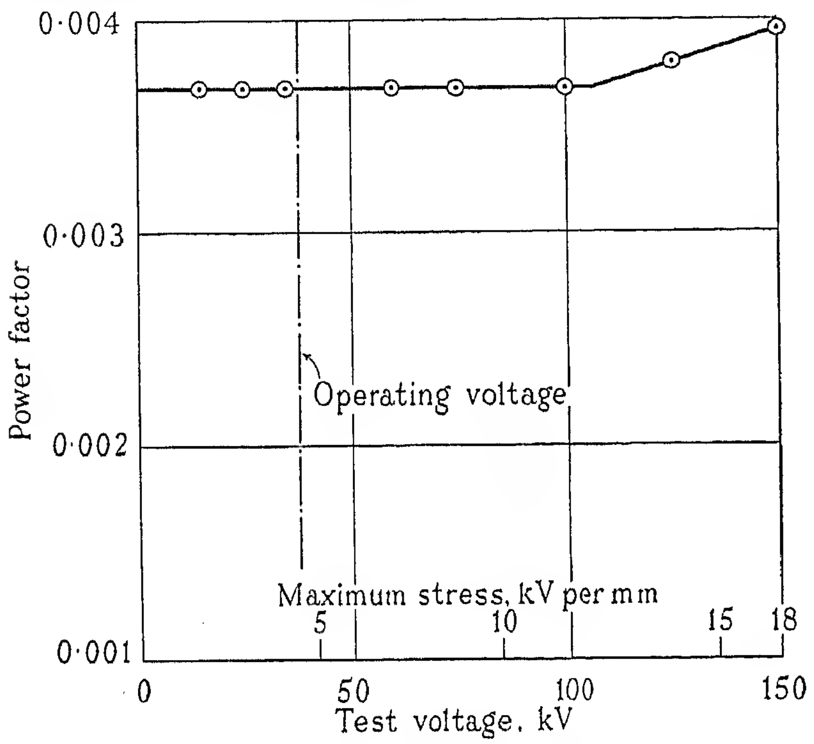

Fig. A.—Power-factor/voltage characteristic of 66-kV cable.

Mr. T. G. Partridge: I should like to put one or two questions arising out of Mr. Kibblewhite's paper.

He does not state in the paper the specification of the cable. One presumes that this cable has been drawn in, and not laid direct, but it would be of interest to know definitely.

With regard to the question of the number of joints which have broken down, is any record kept of the actual jointers coupled with each of the breakdowns, enabling one to ascertain whether the trouble can be associated with the work of any particular man? When a jointer is first put on to making 11-kV or 6-kV joints he is worried for a little while, because he has to deal with very small tolerances inside the lead sleeve; the slightest amount of out-of-centre means that he gets only, perhaps, $\frac{1}{8}$ in. of compound between his binder tapes and the inside of the lead sleeve on one side, and $\frac{1}{2}$ in. the other.

Another question which will probably arise on many networks is this: If one is carrying out routine tests at a moderate voltage and is having no trouble, is one likely to contemplate the over-voltage testing suggested by the author? I do not think that any engineer-in-chief of an undertaking would contemplate doing such a thing. I hope that other engineers who are present will give their own experiences with regard to the number of breakdowns where the cable has been designed for the working voltage. I presume that the 5·5-kV cable referred to by the author had given rise to a negligible number of faults before the voltage on it was increased.

Mr. J. C. Quayle: Can the authors explain why the power factor rises if discharge does not take place? It would be of interest if they would indicate what practical difficulty they found concerning the 5th and 7th harmonics of the 50-cycle supply, and how and why these harmonics were eliminated.

Mr. F. H. Sharpe: The discussion on both papers so far has been of a somewhat pessimistic nature; I should like to introduce a note of optimism.

The apparatus put forward by Mr. Arman and Dr. Starr is perhaps at present only in the laboratory stage, and the authors may not have explored its possibilities to the full. They have, however, given us something which we have all awaited—an instrument for detecting incipient insulation failure, we hope ultimately in the field.

Both Mr. Kibblewhite and previous speakers have shown that d.c. testing of cables can be of help, and, although they give little guidance to those of us who have been considering this procedure for use on high-voltage cables, Mr. Kibblewhite's paper will make it easier for the industry to accept this practice—possibly as a routine measure in certain circumstances—when the time is ripe. I should be interested to know whether the tests revealed any relationship between frequency of breakdown and type and operating conditions of cable. For example, did the more heavily-loaded cables fail more easily; how did cables drawn into ducts compare with those laid direct; and did shaped-conductor cables behave better or worse than circular-conductor cables?

Mr. W. Fennell: With regard to the paper by Mr. Arman and Dr. Starr, we should like to see test figures for some of the 33 000-volt belted cables made about 5 years ago. If the equipment described by the authors provides some more knowledge as to the life of these cables we shall be very grateful.

The Mid-Cheshire Electricity Supply Co. has a d.c. testing outfit for use up to 40 000 volts, but we have so far not dared to use it for heavy over-voltage tests. We have several lengths of cable, ordered originally for 3 300 volts, which we have been running at 6 600 volts for quite a long time. We asked the makers what they thought about it, before the voltage was raised, and they did not express any violent antipathy to the idea. These cables have given no trouble at the higher voltage, and our feeling in regard to them has been that we should "let sleeping dogs lie." Now we are assured, from Mr. Kibblewhite's experience, that we are safe in adopting, say, 4 times the designed working voltage for d.c. tests on underground cables.

Mr. E. V. Clark (South Australia) (*communicated*): A point not referred to in Mr. Kibblewhite's paper is the marked superiority of the cables with 0·20 in. dielectric over those with 0·24 in. According to Tables 1, 3, and 5, the former cables with roughly half the length in use have suffered only two breakdowns in service, and one under test, compared with 17 and 27 respectively in the case of the more heavily insulated cables. The dates given of the laying of the cables do not suggest that age

has appreciable influence on this difference. Can the author throw any light on the matter ?

Ignoring cables of 0·18 in. dielectric, which are no longer in use, and these exceptionally good cables of 0·20 in. dielectric, I have endeavoured to check the suitability of the test voltage adopted by computing the virtual faults per annum per mile on the cables of 0·24 in. dielectric, on the purely arbitrary assumption that defects revealed in testing would have developed into faults during the next year. Table A is based on this assumption, the figures being taken from the author's Tables 1, 3, and 5.

This Table certainly suggests that the d.c. testing voltage of 50 kV is somewhat severer than desirable, causing a considerable number of failures under test at points of slight weakness which were quite strong enough to have lasted well over a year under service conditions. The figures, however, are not quite complete, since the author refers to a few defects revealed by tests at 16·5 kV (a.c.), which are not included in his Tables; if they were included it would somewhat raise the figure for 1933. Nevertheless, one may suggest that a test pressure of 40 kV might have been a better choice—a pressure which, as the author points out, would have proved more suitable for the joint boxes. A lower test pressure would naturally make desirable a somewhat more frequent test, in order to give equal immunity from service breakdowns; and an economic choice of test pressure must of course take this into consideration.

Table A

5·5-kV Cables with 0·24 in. Dielectric, used on 11 kV

(*a*) Year	1932	1933	1934	1935
(*b*) Breakdowns in service	9	5	2	1
(*c*) Average miles in use	52	44	31	24·5
(*d*) Breakdowns per annum per 10 miles of cable	1·7	1·1	0·6	0·4
(*e*) Test failures in previous year	0	2	16	9
(*f*) Average miles tested	—	52	44	31
(*g*) Test failures per annum per 10 miles	—	0·4	3·7	2·9
(*h*) Equivalent failures per annum per 10 miles of cable, i.e. (*d*) + (*g*)	1·7	1·5	4·3	3·3

Mr. N. E. G. Hill (*communicated*): The two important factors in the measurement of discharges in dielectrics are the discharge external to the sample and the sensitivity of the detection apparatus. The problem of eliminating external discharge has evidently received much attention from Mr. Arman and Dr. Starr, but it seems probable that the most sensitive detection apparatus has not been used.

Fig. 10 in their paper shows resistances connected in the elements of the high-pass filter. It is stated in the section devoted to the design of the apparatus that these resistances are necessary in order "to smooth out humps in the response curve which are otherwise found to occur." A correctly-designed filter will have a uniform response and negligible attenuation throughout the pass range. If the elements of the filter are incorrectly matched to one another and to the external resistances, then reflection phenomena will occur, giving humps in the response curve. It therefore seems probable that the high-pass filter used by the authors has been incorrectly designed, and an examination of Fig. 10 confirms this view. A simple calculation shows that on the output side the terminal half-section is not matched to the load resistance of 3 700 ohms for frequencies in the pass range. In addition, although the value of the inductance L is not stated, it is to be inferred from the text that the two shunt elements on the right, one consisting of an inductance L in series with a capacitance of 6 μF, and the other of an inductance L in series with a capacitance of 3·07 μF, have been designed for series resonance at 250 and 350 cycles respectively. These elements are not matched to one another.

In smoothing the response curve by means of resistances the authors have of necessity introduced losses in their filter, with the result that the response varies between 0·6 and 0·8 approximately. This is a serious loss of sensitivity which could readily be overcome, without impairing the attenuation characteristic, by modifying the filter design.

No details are given of the band-pass filter mentioned later in the paper, but, if the authors found it necessary to introduce resistance into the elements, faulty design may again be suspected.

Mr. A. N. Arman and **Dr. A. T. Starr** (*in reply*): We agree with Dr. Rayner that the balanced-transformer method of Fig. 4 is most attractive. We actually did put equal resistances across both transformers, but without success. We ascribed the failure to the fact that the load on the left-hand transformer varies with the potentiometer setting, so that it is not possible to obtain a balance at all settings. In addition, stray capacitances made the method difficult to operate.

The sole requirement for the standard condenser of Fig. 5 is that it should be discharge-free; its power factor and capacitance are unimportant. It is usually convenient to use a high-voltage air or compressed-gas condenser such as is used for Schering-bridge measurements.

With regard to the choice of frequency band, we have shown that any frequency band can be chosen with the same result. The narrower the band the easier it is to balance out external discharges, but the less sensitive is the arrangement. The band 11–21 kc was chosen as being well away from power frequencies and narrow enough to balance external discharges without undue loss

of sensitivity. Moreover, it is a frequency band for which filter and amplifier design is comparatively easy.

Mr. Scott suggests that we have not indicated that considerable variations of power factor are possible without the presence of discharge. We would refer him to Figs. 15 and 16, which he seems to have overlooked. With regard to his contention that the paper is concerned primarily with impregnated-paper cables, we wish to make it clear that this is not so. The main purpose of the paper was to explain the methods of measurement. The examples given are by no means exhaustive and are merely to show the type of results which may be obtained.

The question of sensitivity, including the case of a small isolated void, is discussed in detail in the text and in Appendix I.

We agree with Dr. Dunsheath that d.c. testing of cables is safe because, until very high voltages are reached, there is no discharge. It is therefore possible to reach the rupture voltage of the faulty portions without producing ionization damage in the healthy parts. We would suggest that d.c. discharge measurements should be made on healthy samples to determine the voltage at which discharge begins. Any voltage below this can safely be used for d.c. testing on the system.

We are very interested in the correlation of Fig. 16 with the results obtained by Dr. Dunsheath. This is in accordance with expectation.

With reference to Mr. Quayle's question and to Mr. Mildner's suggestion that it is very unlikely that moisture is causing the power-factor variation in Fig. 16, we would point out that our measurements were made in a uniform field between flat plates. Mr. Mildner's Fig. A is taken in a non-uniform field where the effect of moisture is not shown so readily. It is quite certain that the beginning of discharge indicates the start of gaseous ionization.

We wish to point out to Mr. Hill that the irregularities in the response of the filter shown in Fig. 11 are due, not to faulty design, but to the fact that we used ready-made coils of nominal value 68 mH and not accurate to within $\pm$ 5 per cent. The value of the inductances is stated below the Figure. It was not considered worth while getting more accurate coils, but it was preferred to achieve uniform response by the use of swamping resistances. The response level of the filter is quite unimportant in view of the high-gain amplifier which follows it. The tuned circuits for the 5th and 7th harmonics do not cause any appreciable mismatching, because their frequencies are so very much lower than the cut-off frequency. The value of m differs from unity by less than $\frac{1}{4}$ per cent and does not affect the values of the elements. In the band-pass filter special hand-wound coils were made and damping resistances were not required.

Mr. C. Kibblewhite (*in reply*): In reply to Dr. Rayner, the cables referred to as small-dielectric cables were not supplied originally to operate at a voltage of higher than 5·5 kV. In Table 3, the figures on the left-hand denote voltages between conductors and those on the right-hand voltages between conductors and earth. The a.c. test voltage applied was 3-phase, 16·5 kV between conductors. It is the usual practice to discharge cables after a d.c. over-voltage test by flashing to earth through a resistance. We use rods having a resistance of 1·5 megohms; two are used in series if the test voltage is higher than 50 kV. Comparatively gradual discharge is effected in this way, and we have experienced no damage to cables or any other trouble.

Mr. Scott queries the necessity for testing modern 11-kV cables. It is not my purpose to advocate routine testing for conditions in which cables are giving thoroughly satisfactory service; and even where conditions are such that testing may be contemplated, the decision to adopt it or not will no doubt be influenced by the importance of the supplies affected and the adequacy or otherwise of the protective gear in use to clear faults without interruption of supply.

I will deal a little later with the value of the test voltage, which Mr. Scott thinks might well be lower than 5 times the working voltage. The production of apparatus to detect incipient faults at comparatively low test voltages, which Mr. Scott forecasts, would be welcomed in the supply industry, but we can see no sign of it at present and, even if it comes, then faults should be cleared at the very earliest opportunity after detection, and for this purpose the application of a high d.c. voltage is the only practicable agent. Most of our tests were carried out at times when the system load was light and cable temperatures were therefore, as a rule, not greatly in excess of ground temperature at the time of test; beyond this I cannot give any information as to the effect of temperature on the breakdown strength of the cable.

Mr. Nethersole calls attention to the view that damage may be done to a cable by a high-voltage d.c. test which does not actually break the cable down. In the present imperfect state of our knowledge of this subject it would be unwise to be dogmatic, but I can say that the behaviour of cables which have been regularly tested for 3 years and more has given me no reason to think that they have been in any way damaged by testing. I am not in favour of a longer test at a lower voltage, except possibly where the presence of moisture is suspected. I think that if a d.c. test is going to pick out a fault it will do so as soon as the voltage has reached the breakdown value of the remaining effective dielectric at the point of greatest weakness. The appearance of a time element in the breakdown of some of the cables on d.c. test seems in conflict with this view, but I believe that it is associated with the lack of free compound and consequent high gas-content of these old cables.

Dr. Dunsheath may have supplied the clue to this problem in focusing attention on the discharges in dielectrics observed by Messrs. Arman and Starr. Although d.c. discharge takes place at a much higher stress value than a.c. discharge, when it does appear it may produce a gradual decrease in the insulating value of occluded gases and so lead to breakdown of an otherwise sound cable, which would have recovered if the application of test voltage had not been unduly prolonged. Dr. Dunsheath's suggestion that the delayed appearance of d.c. discharge may explain the fact that d.c. over-voltage tests detect weaknesses without damage to sound cable is particularly interesting. Personally, I should have liked to be able to suggest an explanation of this feature of d.c. testing, but I confess that my reticence on the subject, to which Dr. Dunsheath has

referred, was due to inability to offer any adequate theory. It is certainly true that ionization, which is normally understood as being associated with a.c. stress, is absent on a d.c. test, but I hardly think this fact wholly explains the success of d.c. as compared with a.c. testing. As Dr. Dunsheath points out, the appearance of d.c. discharge may be an extremely useful guide in fixing a suitable maximum test voltage and the lower negative discharge recorded by Messrs. Arman and Starr indicates that it would be better for the conductor of a cable on test to be positively charged. In our tests the reverse was the rule.

Returning to Mr. Nethersole's inquiry about a d.c. over-voltage test on a cable at the end of a maintenance period, no doubt this could be agreed upon with the contractor and would serve a useful purpose.

It is interesting to learn that Mr. Siviour has been carrying out d.c. over-voltage tests, although the results he reports are not perhaps very encouraging. Of his three service breakdowns subsequent to test, one at least apparently occurred shortly after test. We also had two disappointing cases (Nos. 19 and 21, Table 3) of breakdowns occurring shortly after test. It is encouraging, however, to find that Mr. Siviour with his extensive operational experience feels satisfied that routine testing can be usefully employed. I recognize the difficulty he points out of taking important sections of ring mains out of commission for test, but one of the great advantages claimed for routine testing is that it enables one to precipitate breakdowns at a time of one's own choosing, with everything required for location and repairs on the spot.

Mr. Mildner suggests an explanation of the flatness of the d.c. breakdown time/voltage curve, but I think the problem requires more particular investigation before a generalization on the lines he suggests can be accepted.

In reply to Mr. Partridge and Mr. Sharpe, most of the small-dielectric cable was laid solid in bitumen in troughing and some short lengths were drawn into conduit, but I cannot say that I have been able to detect any relationship between the method of laying or the loading conditions and the incidence of breakdowns. All the 0·24-in. dielectric cables had sector-shaped conductors with what would nowadays be recognized as unduly sharp edges. On the other hand, about 75 per cent of the 0·2-in. dielectric cable had circular conductors, and I believe that this feature was an important factor in enabling these cables to give so much better results on the higher operating voltage.

Mr. Partridge also refers to joints; nowadays we keep a record of the name of the jointer who makes each high-tension joint, but these records do not go back to the date when many of these old cables were laid, and I have not attempted to relate breakdowns to jointers except in a few cases in which testing has brought to light bad workmanship on the part of men still employed in the locality. The great majority of joint failures on test have resulted from the taping round the ferrule being in contact with the lead sleeve, either left so originally by the jointer or having worked out due to the movement of cores on load. This type of weakness has never given any trouble in service at 5·5 kV, but I have records of a number of joints which have failed for this reason at 11 kV. All our 11-kV joints are now made with a double split micanite tube sprung over the taping at each ferrule to give added security in case of any decentralization of the cores. There was practically no trouble at all on these old cables when they were operating at 5·5 kV, and I am glad to say that we have had very little trouble indeed on cables designed for 11 kV and operating at that voltage.

Mr. Fennell will no doubt continue to let his "sleeping dogs lie," and I hope they may remain quiescent for all time; but should they start to "bark and bite" he may perhaps find his d.c. testing set an effective muzzle.

Mr. Clark points out the better performance of the 0·2-in. dielectric cable. I have mentioned above that about 75 per cent of this cable had circular conductors as compared with the rather badly formed sector-shaped conductors of the 0·24-in. dielectric cable. All the 0·2-in. dielectric cables have been laid since 1918, and their average life is therefore shorter than that of the 0·24-in. type. Furthermore, about 20 per cent of the 0·2-in. dielectric cable was impregnated under pressure, all the rest having been impregnated in unsealed tanks. The 0·2-in. dielectric cable has certainly behaved very well indeed on 11 kV.

I am grateful to Mr. Clark for his interesting analysis of the results in Table A, and I think item (*d*) of this table shows up the good results of routine testing more clearly than any of the tables I prepared myself. I like Mr. Clark's method of deducing the right voltage for testing, and he almost persuades me that 40 kV would have been better than 50 kV. At the same time, if one is attempting to clear all or nearly all faults which would develop into service breakdowns, one must be prepared to break down some weak points (and an 11-kV cable which will fail on direct current at 50 kV is definitely weaker than it should be) which would have stood up in service for quite a long time, perhaps indefinitely. If I had to start another series of routine tests on a cable network similar to that described in the paper, I should prefer to err on the drastic side rather than risk any increase in the incidence of service faults, and I should not hesitate to adopt the voltage of 50–35 kV recommended in the paper.

REMOTE CONTROL OF POWER NETWORKS

By G. A. BURNS and T. R. RAYNER.

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SUMMARY

Brief introductory remarks in Section (1) draw attention to the fact that modern centralized indicator equipment is essential for the economical operation of power distribution networks. The type of equipment described in the paper is covered by two definitions, namely centralized indication equipment and supervisory control equipment. The various facilities usually demanded in practice are outlined. The choice of method and type of signalling channel to be used are discussed, and the need for adequate protection of the signalling channel and equipment against possible high induced voltages is emphasized. A schematic diagram of typical protective apparatus is given.

Section (2) contains an outline description of Strowger automatic telephone apparatus, which is employed on the various schemes of remote supervision and control described in the paper. The characteristics of telephone type relays, polarized and non-polarized, and the operational features of the uniselector (rotary switch) and two-motion selector mechanisms are outlined. The symbols employed in the diagrams are indicated.

In Section (3) the layout of centralized control rooms is discussed, with particular reference to the various types of wall and miniature diagrams employed. The layout of certain control rooms of the British grid systems are given.

The operation of typical circuits employing the uniselector for the remote indication of switch position is described in detail in Section (4). The function of the repeat relay in ensuring that the indications displayed are in accordance with the actual conditions prevailing, is outlined.

The various methods of remote metering, including individual selections, spot readings, and photo-telemetering, are described in Section (5).

The operation of a system of engine-room telegraph signals is described in Section (6).

Section (7) deals with a system of protection of power networks over the signalling circuits by means of automatic telephone apparatus. Characterized by extreme rapidity of operation, with automatic self-checking features, this system is shown adapted successfully to the inter-tripping of circuit breakers.

The operational features of the fundamental circuits are described in Section (8), including the processes of selection, proving the selection, remote control of selected item, and the subsequent signalling of the indication that the intended operation has been effected.

In Section (9) are described the methods of a.c. voice-frequency signalling employed in circumstances where the length of line or make-up of the signalling channel prohibits the employment of d.c. signalling.

The paper finishes with a Conclusion and a Bibliography.

(1) INTRODUCTION

The problem of nation-wide electricity supply has undergone considerable modifications during recent years. Electric power has been applied more and more to a variety of services, with the result that continuity of supply, always the principal aim of supply authorities, has now become essential to the life of the community.

During the period of development in the use of electricity, the economic conditions have become increasingly severe, with the result that the utmost economy must be observed both with respect to capital and running costs.

Economy in capital cost of the industry as a whole entails the reduction of spare plant to a minimum by creating a common pool.

Economy in running costs necessitates the placing of the generating stations in such positions that fuel and water costs are reduced to a minimum, and the installation of efficient generating units. It is also necessary that the system shall be run with the minimum staff possible.

The above factors working together have led to the linking up of generating stations and distributing networks, either by mutual agreement between the various undertakings or by a central body such as the Central Electricity Board.

The capital cost of a complex network of power lines is a very considerable item and it is essential that the greatest possible benefit be obtained from them in practice.

Full use of power lines can be obtained only if the controlling engineer is informed immediately of any change in the conditions of such magnitude as materially affects the power distribution in the network under his control.

In the case of generating stations and transforming stations which are necessarily attended, the control engineer may be informed by telephone of any abnormal occurrence such as the tripping of a feeder switch. If this course is adopted, however, the control engineer is harassed by being compelled to listen to a large number of reports of the same fault, which are often accompanied by more or less unimportant and irrelevant information just at the time when he is extremely busy with major problems. It is therefore highly desirable that he be informed exactly what has happened by some automatic means as quickly as possible.

It is safe to say that, with modern centralized indication equipment, the control engineer usually knows of a switch having tripped before the switchboard attendant himself does, since all signals are arranged to be visible to the control engineer, whereas the switchboard attendant may have to walk along the board.

In the case of transforming stations, the installation of supervisory control equipment will very often save three shifts of attendants for a comparatively small capital outlay.

Essential Definitions

There has been no small amount of confusion with respect to the name given to equipment of the type described in this paper, and it would therefore appear desirable to define more clearly what is intended.

(a) Centralized Indication Equipment

This is designed to inform the control engineer of any change of position of circuit breakers, etc., at a distant point, and usually includes some method of meter reading; also, in some cases, a visual instruction indicator is included to instruct the staffs of individual generating stations to perform certain specified operations.

(b) Supervisory Control Equipment

This is designed actually to close switches or perform other functions automatically by means of signals initiated by the control engineer.

A supervisory control system will naturally always be associated with an indicating equipment in order that the control engineer may be informed that the desired change has taken place.

Facilities Generally Demanded

It is outside the scope of this paper to discuss what indications should be given. This is essentially a matter which must be decided by the operating engineer concerned, and will vary over a wide range of combinations to meet various sets of conditions. It is, however, safe to claim that equipment can be designed to indicate automatically practically every condition that can be observed, as is indicated by the following, by no means complete, list:—

Position of circuit breakers.
Position of isolators.
Position of tap-change gear.
Meter readings.
Steam-pressure readings.
Vacuum readings.
Water-level indications.
Transformer temperatures.
Bearing temperatures.
Visual instruction indicators.

The above represent those facilities which are in common demand, but where circumstances make it necessary many less usual facilities can be added. Thus it is quite simple to transmit, together with the information that a circuit breaker has tripped, the reason for its tripping, either by indicating which fault relay has operated or, where the protection system is complex, by the automatic analysis of the position of a number of fault relays. In the case of time-element relays, it is furthermore possible to transmit the time interval between the incidence of the fault and the closure of the trip circuit.

Another indication which, in some circumstances, might be of considerable value to the control engineer is the weather condition at certain points in the area. This naturally applies chiefly to large areas. The demand may often be foretold with greater accuracy from a knowledge of the light conditions throughout the area. Information of this type can readily be transmitted by incorporating a light-sensitive cell brought into use at the will of the control engineer or, alternatively, arranged to transmit automatically an indication when the illumination falls to a predetermined value.

In at least one supply undertaking a wireless receiving set has been installed for the purpose of receiving time signals. Owing to poor receiving conditions locally, the set was placed some miles away from the control room where a spare telephone circuit happened to exist. The control engineers soon got into the habit of observing the severity of the atmospherics and were thus given some idea as to the probability of thundery weather.

Choice of Method

Turning now to the method by which signals are to be transmitted, the choice will largely be determined by the number of wires required to carry the various signals. It is quite evident that the simplest system would be one in which a separate pair of wires is provided for each signal and meter reading. The cost of such a system would, however, be prohibitive, and it is therefore a requisite feature of the design of a supervisory control system that the number of wires should be reduced to a minimum.

Supervisory control systems may be divided into two main classes. The first class relies for its operation on the alterations of the current transmitted over the line. In one system of this type the transmitting unit consists of a battery across which is placed a potentiometer. By sliding a movable contact up and down the resistance, various proportions of the battery voltage are applied to the line. The line current is measured at both the transmitting and receiving ends and thus all error due to changing line resistance is avoided. There remains, however, a possibility of error due to a shunt resistance across the line which would cause the current through the two instruments to differ. Where the circuits are furnished by a well maintained multi-core cable this is not important, but it becomes unreliable where open-wire telephone circuits are employed.

Practically all other methods of supervisory control use a predetermined number of impulses to effect the selection of the operation, but differ considerably in the manner of application.

One system employs a continuously running distributor at each end of the line. The distributors may be kept in synchronism by one of many possible ways. At each end of the line the distributors are identical and are provided with a number of segments depending upon the number of operations to be performed. A typical arrangement might be:—

Contact 1. Synchronizing impulse.
,, 2. Open or close CB 1.
,, 3. Open or close CB 2.
,, 4. Indicate CB 1.
,, 5. Indicate CB 2.

The synchronizing impulse is required since, in general, it will not be possible to use the power supply for driving the distributors.

In any system of this type it is obvious that absolute synchronism between the sending and receiving ends

of the line is essential, and to avoid faulty operation it is necessary to check for synchronism before closing any given switch. This checking may be done in a variety of ways which need not be discussed here. The following will suffice to outline some of the possibilities.

(*a*) All signals from the control room to the distant station may be transmitted twice, with a suitable interval between, and the circuit so arranged that unless the same signal is received in both positions of the distributor, the signal is ineffective. Alternatively, the second revolution of the distributor may be utilized for the second or confirmatory transmission.

(*b*) A signal received at the distant station may be repeated back to the control point where, if it agrees with that originally sent, it may be re-transmitted to become effective.

(*c*) The receipt of the synchronizing impulse in the correct position may be taken as proof of accurate synchronism and may cause the signal to become effective.

It is not, of course, necessary for the distributors to run continuously, but they may be designed to rest normally on the synchronizing contact, as in start-stop printing telegraph systems. A single impulse of current over the line would then cause both distributors to commence rotating for one or more revolutions as required.

The Signalling Channel

The provision of the signalling channel between the remote station and the control point needs very careful consideration, not because the requirements of the control or indication gear are severe, but rather owing to the large number of alternatives which must receive consideration by the engineer planning the system.

It is quite impossible to lay down any hard-and-fast lines as to the type of circuit to be provided, but no paper on this subject could be considered complete without a brief summary of the various types of circuit which can be employed, and a few remarks as to the advantages and limitations of each type.

Nowadays it may be taken for granted that all important transformer stations, as well as all generating stations, in a network will be linked by a telephone system of some kind or other. This telephone system may be available at all times to the operating company or may take the form of ordinary telephone lines to the nearest telephone exchange. Generally speaking, any telephone circuit is suitable for remote indication and control purposes, but obviously if the circuit is rented from the telephone administration as and when required, special steps will have to be taken to set up a call originating at the transformer-station. If the exchange is an automatic one, this is not difficult, since the supervisory equipment can be designed to dial the number of the control station and ensure that it is connected to the signal-receiving equipment before proceeding to transmit the train of impulses which represent the information it is desired to give to the controlling engineer.

Where, however, the local exchange is manual, the problem is not so simple, since in this case it would be necessary to give the number of the control station verbally by means of a gramophone. This is not, of course, impossible but it would not meet with the approval of telephone administrations, because no way of replying to the operator in the event of an inquiry can be arranged. This scheme, however, might be useful in special cases where the power company may have special privileges.

It is rather difficult to imagine a set of circumstances under which it would be economical and practical to use an exchange line for supervisory services, but it is conceivable that it might be useful in cases where one of the offices of the operating company is on the site of a transformer station. During daytime, the line would be in use for normal telephone calls, and, in the event of any switch tripping on a fault one of the office staff would be instructed to inform the control engineer. At night, however, the office would be unattended and any information as to switch positions, etc., would be conveyed automatically by the supervisory equipment. In any case the information must be delayed by the time taken to set up the call.

Leaving now the case where the line is not continuously available, and turning to the more usual conditions, various methods of providing the signalling channel must be considered.

Private Line.

Undoubtedly the best and most reliable way of providing the signalling channel is by means of an underground cable installed and maintained by the power undertaking. The type of cable used will depend upon local conditions but, as a general rule, telephone cable composed of a number of pairs of paper-insulated air-spaced copper wires, having a loop resistance of 88 or 176 ohms per mile, will be found satisfactory both for signalling and also for the transmission of speech.

Some power companies prefer to use an impregnated type of cable or, again, vulcanized-rubber cable. These are quite satisfactory and are perhaps rather more robust than the air-spaced telephone cable. The attenuation to currents of speech frequencies is, however, much greater due to the wire-to-wire capacitance being increased from, say, $0 \cdot 075\ \mu F$ per mile to something of the order of $0 \cdot 12\ \mu F$ or more per mile.

The size of the conductor will in general be determined by the telephone requirements, but as a general rule there is little object in increasing the size beyond about 20 S.W.G. With this type of conductor the supervisory equipment will operate reliably for distances up to 40 miles or more and the speech requirements can be met by suitably loading the line with inductance at regular intervals.

Unfortunately questions of cost often rule out the underground cable network, and some less expensive circuit has to be adopted. A large number of undertakings employ a telephone cable carried overhead on the same poles as the main power line, or, alternatively, open-wire telephone lines are carried on the power-line towers. Either of these types of circuit is quite suitable for supervisory control, but special precautions must be taken to prevent damage to the equipment due to the large induced voltage under fault conditions, and, in the case of the open-wire lines, to protect both the

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Choice of Method

Turning now to the method by which signals are to be transmitted, the choice will largely be determined by the number of wires required to carry the various signals. It is quite evident that the simplest system would be one in which a separate pair of wires is provided for each signal and meter reading. The cost of such a system would, however, be prohibitive, and it is therefore a requisite feature of the design of a supervisory control system that the number of wires should be reduced to a minimum.

Supervisory control systems may be divided into two main classes. The first class relies for its operation on the alterations of the current transmitted over the line. In one system of this type the transmitting unit consists of a battery across which is placed a potentiometer. By sliding a movable contact up and down the resistance, various proportions of the battery voltage are applied to the line. The line current is measured at both the transmitting and receiving ends and thus all error due to changing line resistance is avoided. There remains, however, a possibility of error due to a shunt resistance across the line which would cause the current through the two instruments to differ. Where the circuits are furnished by a well maintained multi-core cable this is not important, but it becomes unreliable where open-wire telephone circuits are employed.

Practically all other methods of supervisory control use a predetermined number of impulses to effect the selection of the operation, but differ considerably in the manner of application.

One system employs a continuously running distributor at each end of the line. The distributors may be kept in synchronism by one of many possible ways. At each end of the line the distributors are identical and are provided with a number of segments depending upon the number of operations to be performed. A typical arrangement might be:—

Contact 1. Synchronizing impulse.
,, 2. Open or close CB 1.
,, 3. Open or close CB 2.
,, 4. Indicate CB 1.
,, 5. Indicate CB 2.

The synchronizing impulse is required since, in general, it will not be possible to use the power supply for driving the distributors.

In any system of this type it is obvious that absolute synchronism between the sending and receiving ends

of the line is essential, and to avoid faulty operation it is necessary to check for synchronism before closing any given switch. This checking may be done in a variety of ways which need not be discussed here. The following will suffice to outline some of the possibilities.

(a) All signals from the control room to the distant station may be transmitted twice, with a suitable interval between, and the circuit so arranged that unless the same signal is received in both positions of the distributor, the signal is ineffective. Alternatively, the second revolution of the distributor may be utilized for the second or confirmatory transmission.

(b) A signal received at the distant station may be repeated back to the control point where, if it agrees with that originally sent, it may be re-transmitted to become effective.

(c) The receipt of the synchronizing impulse in the correct position may be taken as proof of accurate synchronism and may cause the signal to become effective.

It is not, of course, necessary for the distributors to run continuously, but they may be designed to rest normally on the synchronizing contact, as in start-stop printing telegraph systems. A single impulse of current over the line would then cause both distributors to commence rotating for one or more revolutions as required.

The Signalling Channel

The provision of the signalling channel between the remote station and the control point needs very careful consideration, not because the requirements of the control or indication gear are severe, but rather owing to the large number of alternatives which must receive consideration by the engineer planning the system.

It is quite impossible to lay down any hard-and-fast lines as to the type of circuit to be provided, but no paper on this subject could be considered complete without a brief summary of the various types of circuit which can be employed, and a few remarks as to the advantages and limitations of each type.

Nowadays it may be taken for granted that all important transformer stations, as well as all generating stations, in a network will be linked by a telephone system of some kind or other. This telephone system may be available at all times to the operating company or may take the form of ordinary telephone lines to the nearest telephone exchange. Generally speaking, any telephone circuit is suitable for remote indication and control purposes, but obviously if the circuit is rented from the telephone administration as and when required, special steps will have to be taken to set up a call originating at the transformer-station. If the exchange is an automatic one, this is not difficult, since the supervisory equipment can be designed to dial the number of the control station and ensure that it is connected to the signal-receiving equipment before proceeding to transmit the train of impulses which represent the information it is desired to give to the controlling engineer.

Where, however, the local exchange is manual, the problem is not so simple, since in this case it would be necessary to give the number of the control station verbally by means of a gramophone. This is not, of course, impossible but it would not meet with the approval of telephone administrations, because no way of replying to the operator in the event of an inquiry can be arranged. This scheme, however, might be useful in special cases where the power company may have special privileges.

It is rather difficult to imagine a set of circumstances under which it would be economical and practical to use an exchange line for supervisory services, but it is conceivable that it might be useful in cases where one of the offices of the operating company is on the site of a transformer station. During daytime, the line would be in use for normal telephone calls, and, in the event of any switch tripping on a fault one of the office staff would be instructed to inform the control engineer. At night, however, the office would be unattended and any information as to switch positions, etc., would be conveyed automatically by the supervisory equipment. In any case the information must be delayed by the time taken to set up the call.

Leaving now the case where the line is not continuously available, and turning to the more usual conditions, various methods of providing the signalling channel must be considered.

Private Line.

Undoubtedly the best and most reliable way of providing the signalling channel is by means of an underground cable installed and maintained by the power undertaking. The type of cable used will depend upon local conditions but, as a general rule, telephone cable composed of a number of pairs of paper-insulated air-spaced copper wires, having a loop resistance of 88 or 176 ohms per mile, will be found satisfactory both for signalling and also for the transmission of speech.

Some power companies prefer to use an impregnated type of cable or, again, vulcanized-rubber cable. These are quite satisfactory and are perhaps rather more robust than the air-spaced telephone cable. The attenuation to currents of speech frequencies is, however, much greater due to the wire-to-wire capacitance being increased from, say, $0\cdot075\ \mu F$ per mile to something of the order of $0\cdot12\ \mu F$ or more per mile.

The size of the conductor will in general be determined by the telephone requirements, but as a general rule there is little object in increasing the size beyond about 20 S.W.G. With this type of conductor the supervisory equipment will operate reliably for distances up to 40 miles or more and the speech requirements can be met by suitably loading the line with inductance at regular intervals.

Unfortunately questions of cost often rule out the underground cable network, and some less expensive circuit has to be adopted. A large number of undertakings employ a telephone cable carried overhead on the same poles as the main power line, or, alternatively, open-wire telephone lines are carried on the power-line towers. Either of these types of circuit is quite suitable for supervisory control, but special precautions must be taken to prevent damage to the equipment due to the large induced voltage under fault conditions, and, in the case of the open-wire lines, to protect both the

apparatus and the user against the possibility of actual contact between the live power wire and the telephone line in the event of a fracture taking place in the power line.

Considering first the aerial cable, this will usually be lead-covered and carried on a catenary wire. The lead sheath should be frequently earthed throughout its length in order to reduce to a minimum the current flowing along the sheath.

Under these conditions the electrostatic induction can be neglected, as can also the voltage electromagnetically induced in the telephone loop. There remains, however, a voltage induced in the telephone circuit which will be an end-to-end voltage on both the go and return wires in parallel. That is to say, if the two ends of the telephone circuit were earthed, a current would flow from earth at one end along all the wires in the cable in parallel to earth at the far end.

Under normal working conditions this induced voltage is quite small and is only due to the residual flux from the power line caused by the unequal distance of the three phases from the telephone line and also by any lack of balance in the power circuit.

Under fault conditions the end-to-end voltage will become very large and will, in fact, be practically equal to the voltage existing between the faulty phase and earth, and, unless means are provided for safely discharging the line to earth, serious damage will be caused to the supervisory apparatus and also in the cable itself.

An alternative is to place a low-resistance inductance of, say, 100 henrys across the line and connect the exact centre point of this inductance to earth. By this means a low-impedance path to earth is provided for all voltages travelling in the same direction on the two wires, but a high impedance is maintained to loop voltages. Under these circumstances it will, of course, be essential to employ alternating current for signalling purposes. This current may be of power frequency or of voice frequency, depending upon the prevailing circumstances. The use of alternating current involves some extra expense in the supervisory equipment, and also leads to some complication of the relevant circuits, with the result that an alternative method of protection has been devised; this has proved very satisfactory in actual practice.

Two gas-discharge tubes are placed between the two wires and earth, whilst a third tube, preferably having a lower flash-over voltage, is placed across the two lines. The object of the third tube is to prevent a large loop current flowing in the event of there being a difference between the characteristics of the earth tubes.

If it were possible to regard the impedance to earth of the terminal apparatus as infinite, no additional apparatus would be required. In practice, however, this is not the case as, even if the insulation be of a very high order, the cabinet together with its associated batteries will have a considerable capacitance to earth which will give rise to heavy currents through portions of the signalling equipment. This current will usually have its major component at some harmonic frequency of the power frequency, since the power voltage during a fault will be very rich in harmonics.

A satisfactory method of reducing this capacitance current to reasonable proportions is to place a two-winding inductance in series with the line as shown in Fig. 1. It is essential that the two windings be very closely coupled in order that speech loss shall be negligible. The two windings must also be accurately balanced in all respects in order that no cross-talk or noise currents may be introduced into the telephone circuit.

The above remarks apply equally well to the open-wire telephone circuit, except that in this case we have a much larger induced loop voltage due to the impossibility of transposing the wires as accurately as the wires in a cable are twisted, and also to the inevitably unequal insulation resistances of the two lines. In addition, it is necessary to cater for the possibility of actual contact between the power line and the telephone line. This makes it essential from a supply point of view to isolate completely the signalling equipment, which is normally within reach of the staff, from the telephone line. Under normal working conditions there will, moreover, be a considerable electrostatic potential between the two wires equally and earth. This voltage is due to the residual electrostatic field existing at the level at which the telephone wires are run, and can only be reduced by adding an earthed screening wire near

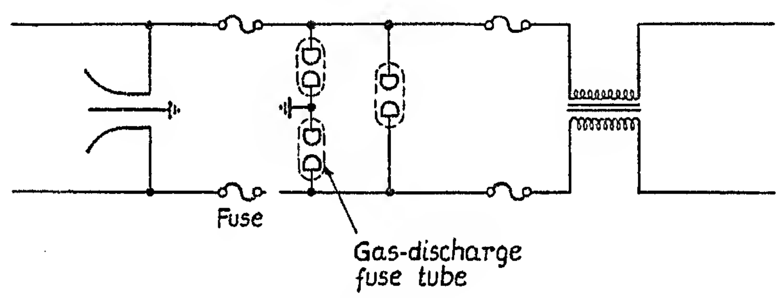


Fig. 1

to the telephone wires and between them and the power circuits, or by transposing the power circuit to change the phase of the residual field.

If alternating-current signalling is adopted, an isolating transformer insulated for the line voltage is inserted between the line and the apparatus rack. This transformer will, as a rule, be protected by fuses and spark gaps on the line side and on the apparatus side by normal telephone protection equipment, with or without the addition of gas-type discharge tubes.

Where it is desired to retain d.c. signalling, no transformer is possible in the signalling circuit and the necessary isolation has to be attained by means of relays capable of withstanding the line voltage between their coils and contacts.

Line Hired from Telephone Administration.

In some cases, notably all the signalling systems in connection with the British grid, private lines have not been erected but signalling channels have been hired from the telephone administration.

Under these conditions protection again becomes necessary, but for a different reason. All circuits in a normal telephone network employ very low voltages on the line, usually not exceeding 50 volts. In any large power system there is always the possibility of an instantaneous rise in the potential of the station

earth above zero which may, under severe fault conditions, reach undetermined but undoubtedly high values far in excess of 50 volts.

Furthermore, the possibility of breakdown in the current or potential transformers, giving rise to high voltages in some portion of the metering or signalling equipment, cannot be entirely ignored.

The British Post Office specify that where any signalling apparatus is connected to their lines the line terminals shall withstand a test pressure of up to 15 000 volts to any portion of the equipment connected to either the station earth or any power supply. Where the station voltage does not exceed 33 kV this test pressure is reduced to 3 750 volts. Where a.c. signalling is in use, a suitably insulated transformer between the line and signalling apparatus provides all the protection necessary, but when d.c. signalling is employed it is again necessary to provide a set of relays with high insulation between coils and contacts. Fig. 2 shows such a group of relays in schematic form.

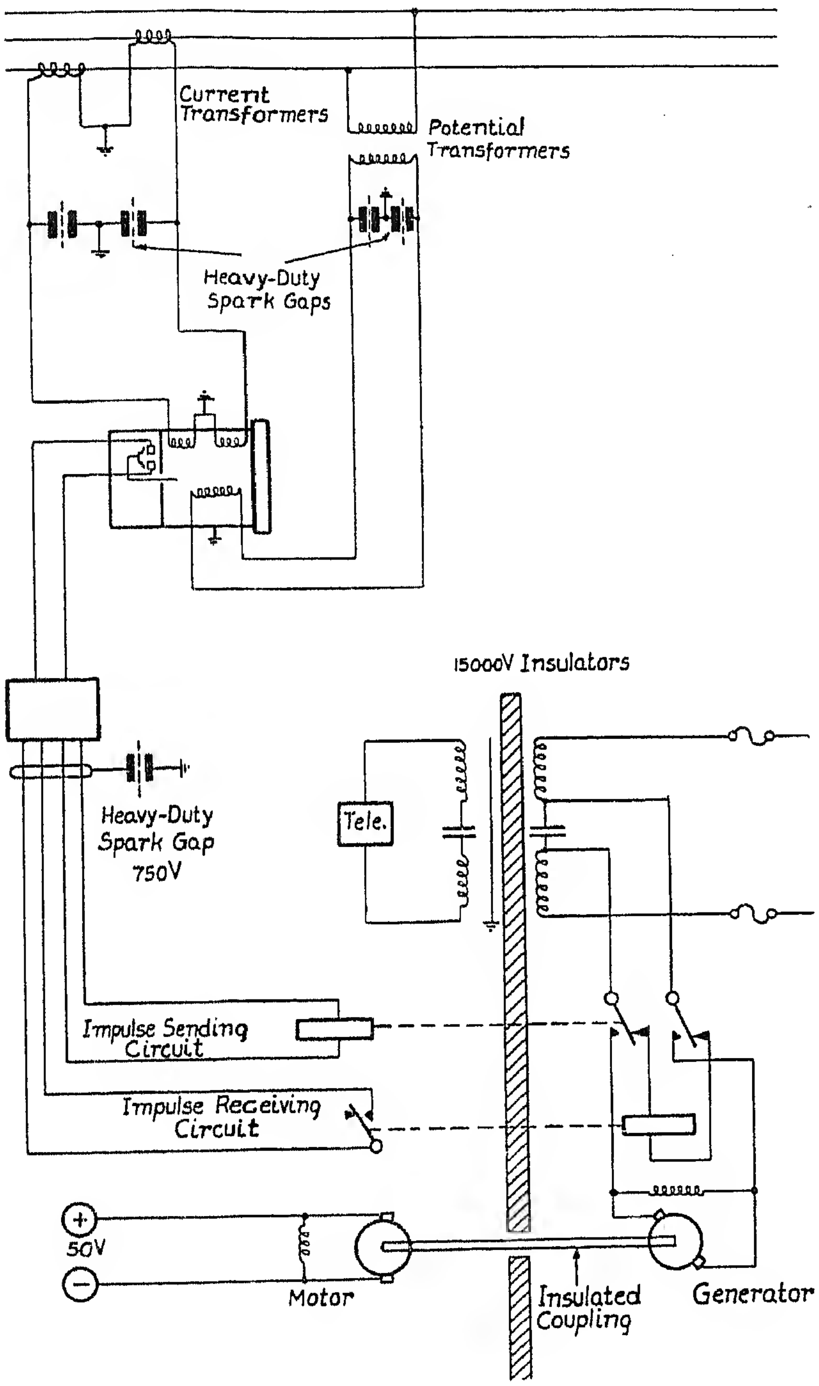


Fig. 2

(2) THE APPARATUS EMPLOYED IN REMOTE SUPERVISION AND CONTROL

In the various schemes of remote supervision and control detailed in this paper, the apparatus used is identical with that employed in the Strowger system of automatic telephony. In addition many fundamental methods of circuit operation used in automatic telephony find their application also in the newer art.

Fig. 3(*a*) represents the general type of relay employed. A is the armature pivoted to a bracket rigidly fixed to the heel piece HP which carries the core C surrounded by the operating winding. A carries an extension *a*, the free end of which is provided with an insulated knob adapted, when A is attracted, to operate the contact springs CS which are mounted between layers of insulating material, the assembly being bolted to the heel piece HP. Fig. 3(*b*) shows how such a relay is indicated in diagrams; Fig. 3(*c*) shows a simple make contact; Fig. 3(*d*) a break contact; Fig. 3(*e*) a break-make group; Fig. 3(*f*) a make-before-break combination; and Fig. 3(*g*) indicates how, by the interposition of a buffer B of insulating material, the upward thrust of the extension piece *a* may be made to operate two groups of springs 1 and 2. By suitable choice of the length of the buffer B a delay interval can be caused to exist between the closure of contact groups 1 and 2.

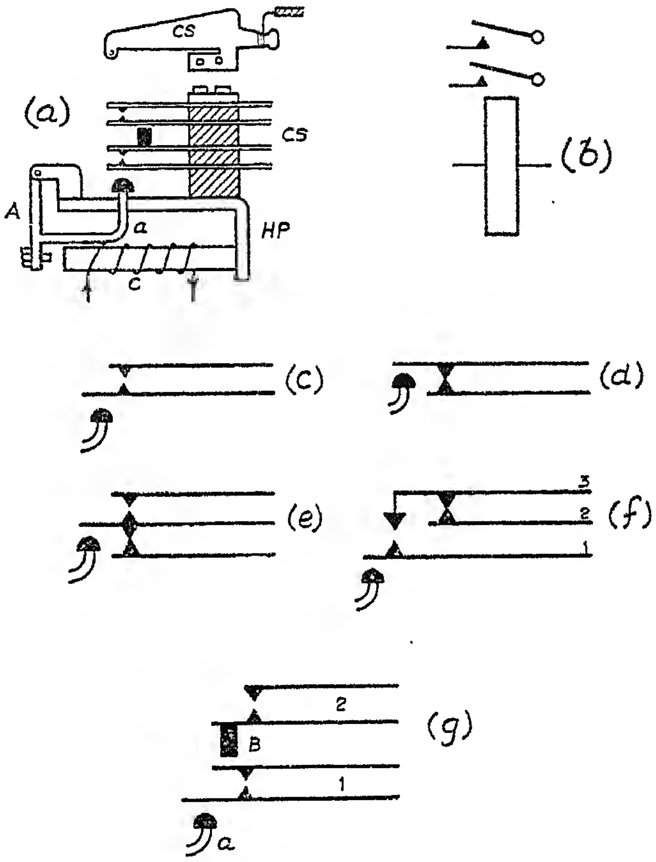


Fig. 3

Fig. 4(*a*) shows a type of relay similar to that of the previous figure, in which a solid copper slug surrounds the core at the armature end. When a current is switched on, the rising flux gives rise to Foucault currents in S which exert a demagnetizing effect, and a period of time elapses before sufficient flux reaches the armature A to cause operation. This delay in operating can be varied by altering the tension given to the contact springs and by varying the dimensions of the slug itself. When the current is switched off,

the decrease in flux generates current in the slug in such a direction that the relay tends to remain in the operated condition. It is thus slow to operate and slow to release. Such a relay is indicated in diagrams by a solid black

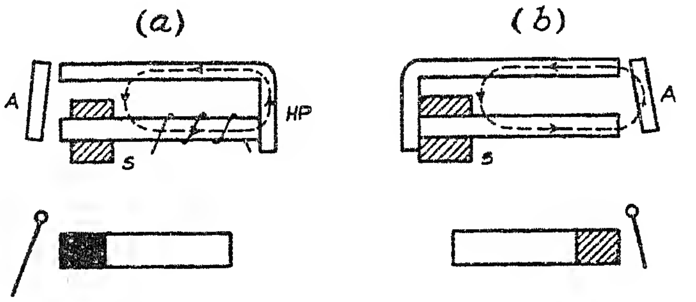


Fig. 4

rectangle at one end, as shown in the lower part of Fig. 4(*a*). In Fig. 4(*b*) the slug is at the heel-piece end of the core, and the initial flux growth takes place as shown in the sketch. Armature A pulls up quickly,

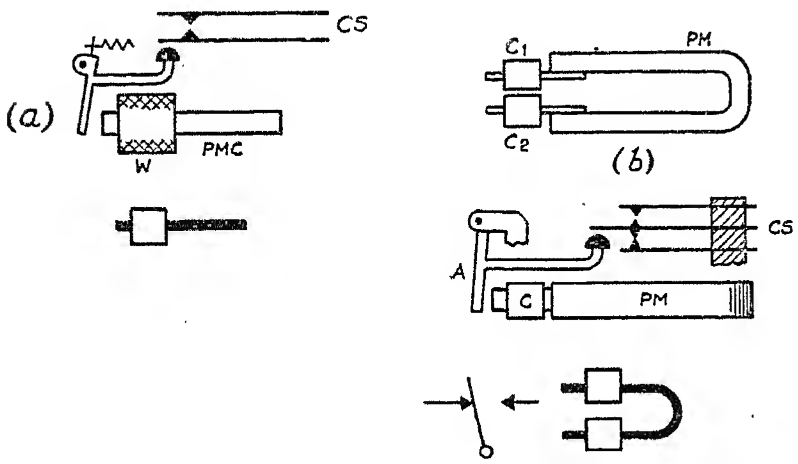


Fig. 5

but the effect of the slug will make the relay slow to release. In diagrams this type is indicated by the hatched rectangle seen in the lower part of Fig. 4(*b*). In cases where a relay is sometimes required to have a slow-to-operate or slow-to-release feature, an ordinary winding is provided which is short-circuited or open-circuited by the operation of another relay contact.

Two types of polarized relay are employed. Fig. 5(*a*) shows one type in which the core is of cobalt steel and is permanently magnetized. Its diagrammatic form is indicated in the lower part of the diagram. Fig. 5(*b*) is a type of polarized relay in which the exciting coils c_1, c_2 are mounted on two extensions or pole-pieces of a permanent magnet PM. This relay has the advantage that it will " stay put " in the position last placed until a current in the reverse direction is received. The contact springs are thus firmly held in one or the other of two positions although the operating current is only transient. This type of relay is employed to a considerable extent in remote supervisory control systems and has proved highly satisfactory. Its diagrammatic representation is indicated in the lower part of the figure.

Fig. 6 represents diagrammatically a type of rotary-switch uniselector largely used in both automatic telephony and remote supervisory control. A shaft S carries two or more wipers W_1, W_2 rigidly fixed to it and rotated through the agency of a ratchet wheel RW driven by a feed pawl FP pivoted to a bell crank BC which is itself pivoted to the frame of the switch at x. The upper end of the bell crank carries an armature A which is attracted each time the driving magnet DM is pulsed by a current. When A is attracted, FP moves idly over one tooth of RW, and during the stroke of A energy is stored in a leaf spring LS. LS is provided with an insulated buffer B which, towards the end of the stroke of A, opens the interrupter springs for a purpose which is later made apparent. At the termination of the current pulse in DM, the energy stored in the leaf spring LS restores the bell crank BC to normal. In doing so, FP pulls the ratchet wheel RW round clockwise through the space of one tooth, and with it shaft S and wipers W_1 and W_2. As the wipers are stepped round in response to a train of impulses in DM, their tips make contact

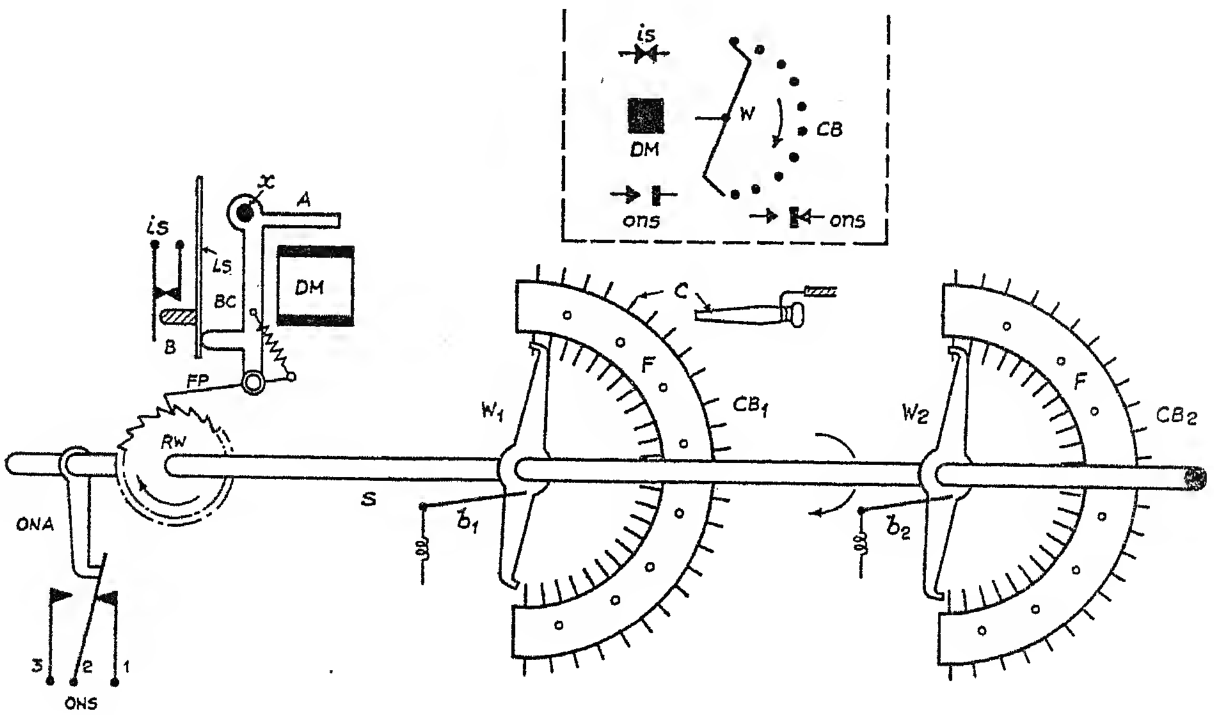


Fig. 6

in turn with a number of contacts C radially disposed and held between insulating strips clamped between metal plates F. Continuous connection with the wipers is maintained by means of brushes b_1 and b_2. The wipers are double-ended and the tips come into operation alternately at each half revolution. As many as 8 wipers and contact banks may be used in connection with one ratchet-and-pawl mechanism. At the left-hand end of the shaft an arm ONA is rigidly fixed. With the switch in the home or normal position this arm presses contacts 1 and 2 together as shown in the diagram.

Immediately the switch moves off-normal, the connection between ONS 1 and 2 is broken and is made between 2 and 3.

It will be noted that it is the de-energization of driving magnet DM which steps the switch wipers on one step, and this method of operation is termed "reverse drive." The symbolic representation of such a switch is shown in the inset.

By using single-ended wipers [Fig. 7(*a*)] the capacity

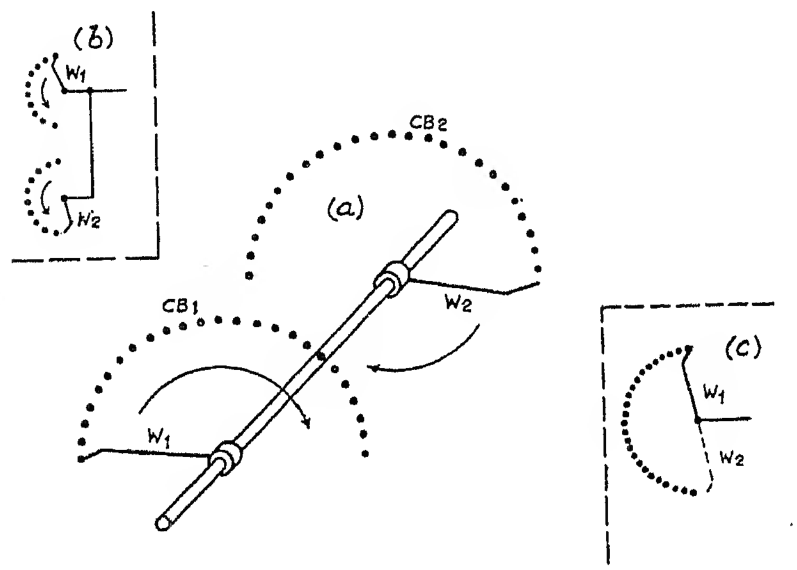


Fig. 7

of the switch is doubled while keeping the diameter of the contact bank the same. Figs. 7(*b*) and 7(*c*) show methods of representing such a switch in circuit diagrams.

Recently, the well-known Strowger double-motion selector or co-ordinate switch has been employed in remote supervisory control schemes. In this switch (Fig. 8) 10 rows or "levels" of contacts are arranged in semi-circular paths, and the shaft carrying the wiper W is moved vertically through 1 to 10 steps to gain access to any desired level and is then rotated from 1 to 10 rotary steps to reach the desired contact. The great advantage of this switch is that the maximum number of steps to reach any one of 100 contacts is 20 only.

The apparatus—relays and selectors—is mounted on angle-iron racks, and the connecting cabling is carried out in accordance with standard telephone-exchange practice.

(3) THE CONTROL ROOM

The control of electrical power has undergone in the course of recent years a physical change which is reflected in the control-room arrangements of the more modern power stations.

The gallery with its switchboard in the engine house is disappearing, and in its place there is the control room with remote electrical operation and indication of the switches.

With this change and the more convenient layout, it has been possible to install a system diagram. This diagram, in many cases, consists of a large wooden board painted white with a mimic diagram of the network complete with switches and isolators depicted in colours. The diagram is usually hand-dressed with small discs

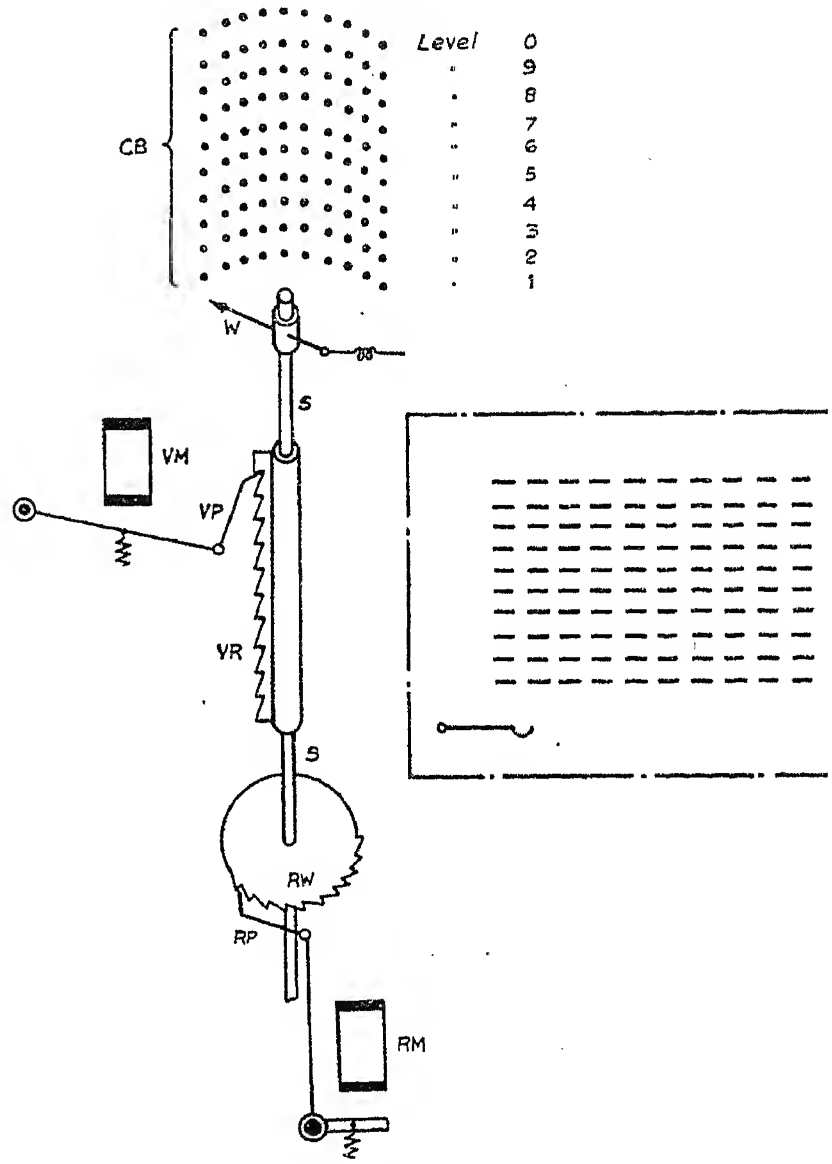


Fig. 8

in various colours which may be hooked on to, or plugged into, it at suitable places. For example, discs may be used to denote that a switch is closed or open, or that a line is earthed, or under repair with men working on it.

Where the network is large it is, of course, advisable that in an emergency all this information should be available to the person responsible for control, but it is vital that the information on the diagram should be correct and easily readable.

Several methods have been developed with these objects in view, chief among which are:—

(1) Illuminated diagrams.
(2) Semaphore diagrams.
(3) Miniature diagrams.
(4) Lamp indicator diagrams.
(5) Built-up diagrams using either semaphores or lamps or a combination of both.

The main advantage of any of the above schemes is that the changes to the diagram are made electrically from the control engineer's desk and can be carried out with a minimum of effort as soon as the information concerning the change of condition of the network is to hand.

Illuminated Diagrams.

Several methods of providing illuminated diagrams are in existence. In some instances the whole system is mapped out in neon tubes which are lit according to whether or not the various lines are alive. This arrangement, whilst spectacular, must be rather trying to live with, and it suffers also from the disadvantage that only the " in " and " out " signals can be shown.

Another method is to insert some semi-opaque material in the panels, with lamps behind. Such a scheme is rather more restful and has been developed so that each of the lines may be caused to light up in any of three colours, thus adding to the amount of information that can be displayed.

Probably the most effective illuminated diagram is one built up of glass panels on the back of which is painted the ground colour of the diagram, leaving the lines of the diagram plain. The diagram is illuminated by coloured lamps set behind the glass in compartments, and suitably designed so that only the necessary amount of diagram is lighted in each compartment. This method gives a very clear diagram and is very restful. The main technical advantage, however, is that unless the diagram is exceedingly cramped, several colours may be used so that very complete information may be displayed. This same type of diagram has been built with metal panels in which the diagram is cut out, the light reflections from the white walls of the compartment causing the openings in the panels to appear as clear-cut coloured lines.

Semaphore Diagrams.

The most common type of semaphore diagram is that using the two-position indicator. The indicator consists of an electrically operated disc with a line painted across it. This disc is rotated so that the line on it either forms a part of the lines of the system or is 90 degrees to the system line with a break each side. Diagrams of this type, whilst being comparatively cheap, suffer from the limits of the information that can be displayed and have to be hand-dressed for special conditions, discs being inserted in special holes drilled in the diagram and the indicators. A more advanced type of diagram is one in which the indicators display four or six different signals. Indicators of this type usually rotate a drum fitted edgewise into the panel, the drum being painted in sections. These indicators can be of quite small dimensions. For instance, an indicator having 6 positions and mounting on $1\frac{1}{2}$-in. centres, would display a signal $\frac{3}{4}$ in. square.

One advantage that a semaphore indicator board has over any type of illuminated board is that it consumes no power except when it is actually being changed.

Lamp Indicator Diagrams.

The lamp indicator type of diagram has all switches represented by a red and green lamp or by a device which shows a red or green signal through a common aperture. The limitations of this type of diagram are mainly that only two types of signal can be displayed conveniently, although for temporary conditions a flashing signal can be given.

Built-up Diagrams.

These are so designed that changes or extensions to the network can readily be recorded on the diagram. Such changes are not easily added to the more common types of diagram, consequently the information portrayed is often out of date, or the system diagram is patched up with some temporary information. The built-up diagram consists of numerous small plates, each exactly the same size and mounting on similar centres. The plates carry various devices with many symbols for isolators, circuit breakers, generators, transformers, earthing devices, and rectifiers, in addition to lines which are used to show busbar feeders. The circuit breakers and isolators may be represented by 2- and 4-position indicators or red or green lamps. The transformer device may be just a symbol or it may carry a lamp illuminated to show when the transformer is energized.

All these plates are assembled on a framework to build a diagram of any design, and it will be obvious that should it become necessary to modify the diagram as the system changes, such modifications can readily be carried out.

For the electrical connections to the devices, special jumper arrangements are provided so that wiring changes can be carried out with ease.

This type of diagram usually has all the devices mounted on square plates and it will be seen that the appearance is quite neat despite the numerous screwheads which are visible, holding the plates in position. A background of black has been chosen to facilitate matching when extensions occur and also to obscure as much as possible the numerous joints which of necessity are present.

Setting-up Electrical Diagrams.

The setting of the diagram should be done by the circuit breakers themselves where possible by means of auxiliary contacts, or by supervisory indication when such is economical.

In circumstances where neither of these arrangements is feasible for the whole system, the devices may be set from the control desk on receipt of telephone information from outlying stations. One method of setting the diagram is to allot a number to each switch and to dial the number on an ordinary telephone dial to select the device to be operated, the operation being carried out by means of push-buttons.

If the device selected is of the 4- or 6-position type, it may be necessary to depress the push-button several times until the mechanism displays the correct signal.

A much better way of setting the diagram is, however, by means of a miniature diagram.

Miniature Diagrams.

In this instance a complete diagram of the system is built on a table or as part of the control desk, the circuit breakers, etc., being represented by small turn-

keys. Although this diagram can only control a main diagram fitted with 2- or 3-position indicators, it has the very definite advantage that major switching operations can be planned in advance.

Each turn-key is fitted with contacts for selecting the "in" or "out" position of the device on the main diagram, but the actual change to the diagram does not take place until a small operating push-button associated with a station or group of switches is depressed.

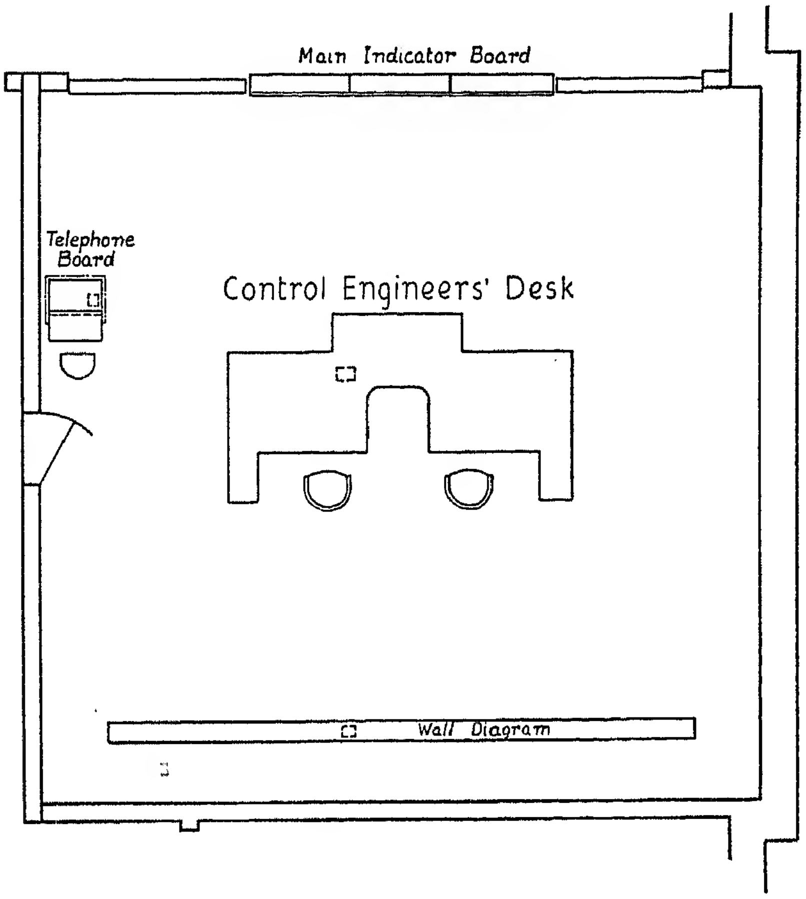


Fig. 9

In many cases the use of two complete diagrams of the system cannot be justified, and under these conditions the miniature diagram only is installed and no contacts are fitted to the turn-keys.

The miniature diagram may be easily dressed to show any abnormal conditions which may exist on the system.

Control Rooms on the British Grids

It is proposed to describe in this paper the salient features of the control rooms of the Central Scotland, N.W. England, and S.W. England grids, as they all express different viewpoints on the subject of control-room practice.

The Scotland Control Room (Fig. 9).

Fig. 9 shows the layout of the control equipment for the Scotland area. The condition of each of the 132-kV oil circuit-breakers is shown by a red and green lamp on the indicator board, directly in front of the control engineers. This main indicator board also carries the transformer-tap position indicators, together with the instruments reading the exchange of power between the various stations and the grid.

The control desk accommodates two engineers and has a miniature diagram of the system in the centre portion. The diagram is raised slightly above the desk-level, and miniature turn-key indicators are used to acknowledge all circuit-breaker changes automatically indicated on the main indicator board. This arrangement ensures that the miniature diagram, which is hand-operated, is always kept up to date.

In addition to the 132-kV switch positions, the diagram also has turn-key indicators to represent all the 132-kV isolators and earthing switches, together with the more important low-voltage switchgear.

The turn-keys are used to operate semaphores in a wall diagram mounted behind the control engineers.

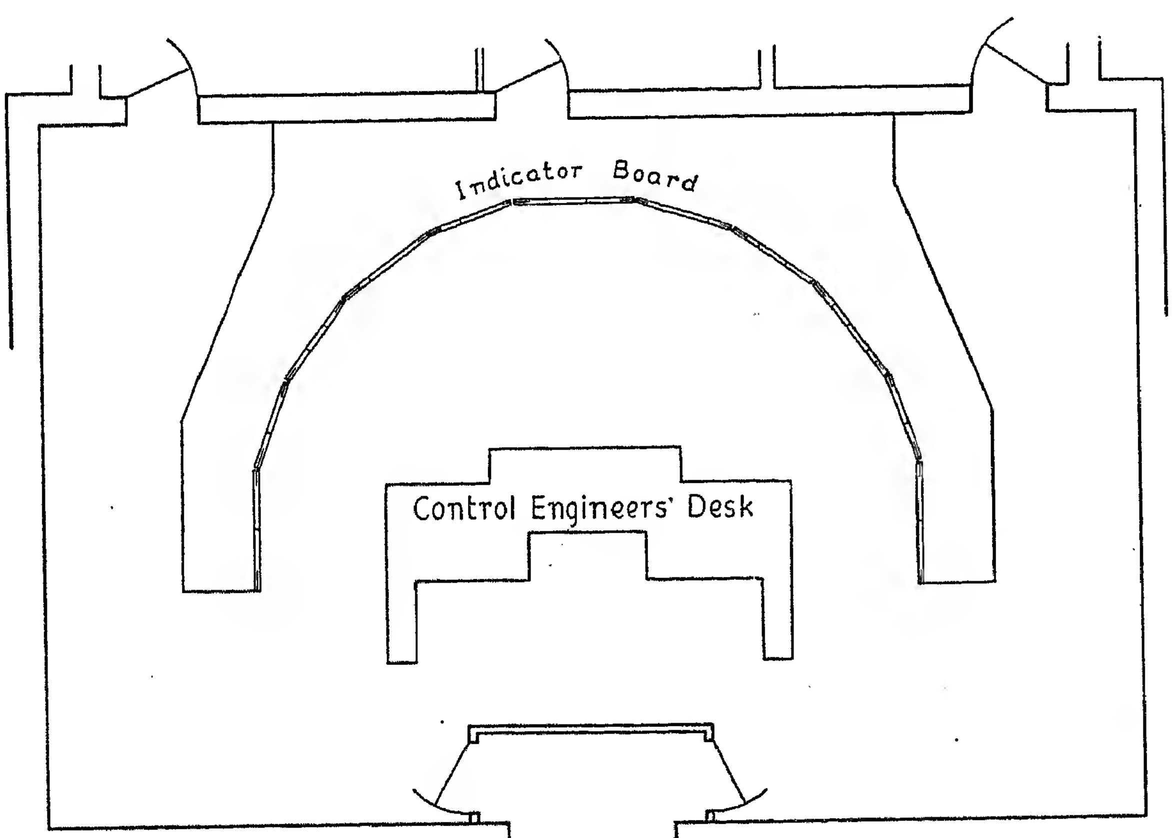


Fig. 10

As this is a replica of the miniature diagram on a large scale, it shows all switch and isolator positions at a glance.

The North-West England Control Room (Fig. 10).

This control room is similar to the Scottish control room in that the main indicator board carries the 132-kV oil circuit-breaker indications, the transformer tap indicators, and the megawatt and megavar instruments, but in addition the 132-kV isolator and earthing switch positions have been added, these being controlled from the miniature diagram.

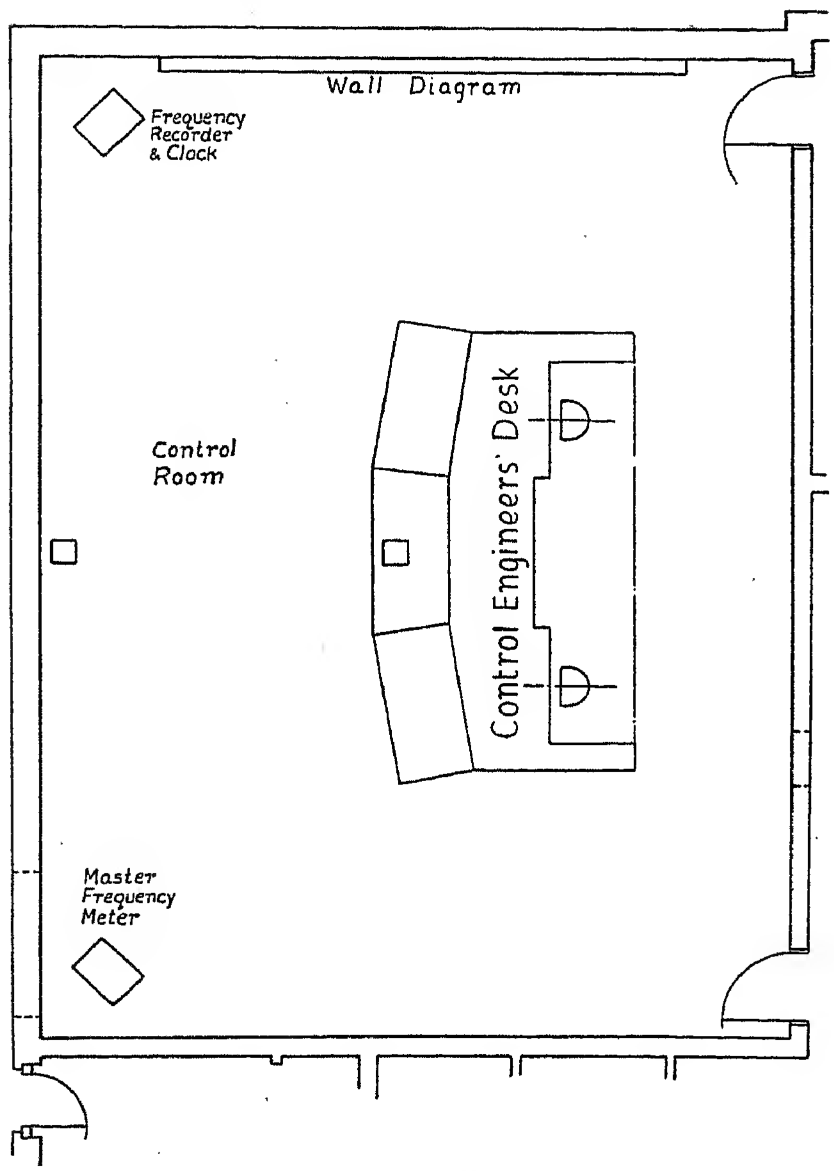


Fig. 11

The miniature diagram is also fitted with turn-key indicators, depicting all the main lower-voltage switchgear and earthing switches, but no wall diagram is installed.

The South-West England Control Room (Fig. 11).

The tendency to rely on a miniature diagram has been carried a stage further in the design of the control room for this area.

The main indicator board has been considerably condensed to form part of the control desk. Whilst still indicating the 132-kV switch positions, the transformer-tap positions, and the load transfer, it does not show the interconnecting lines between the various stations.

The miniature diagram carries the complete circuit arrangements of the area, and is the main system diagram.

In addition to the miniature diagram a completely hand-operated wall diagram is installed, which is used to indicate the normal position of the switchgear at the time, and is also available for instructional purposes.

(4) THE UNISELECTOR (ROTARY SWITCH) AS IMPULSE SENDER AND RESPONDER

Referring to Fig. 12(*a*), one contact bank CB of a single-motion rotary switch is shown in which all of the contacts, except the first on which the wiper W normally rests, are commoned and connected to the positive side of the battery. A pulsing relay PU is connected to

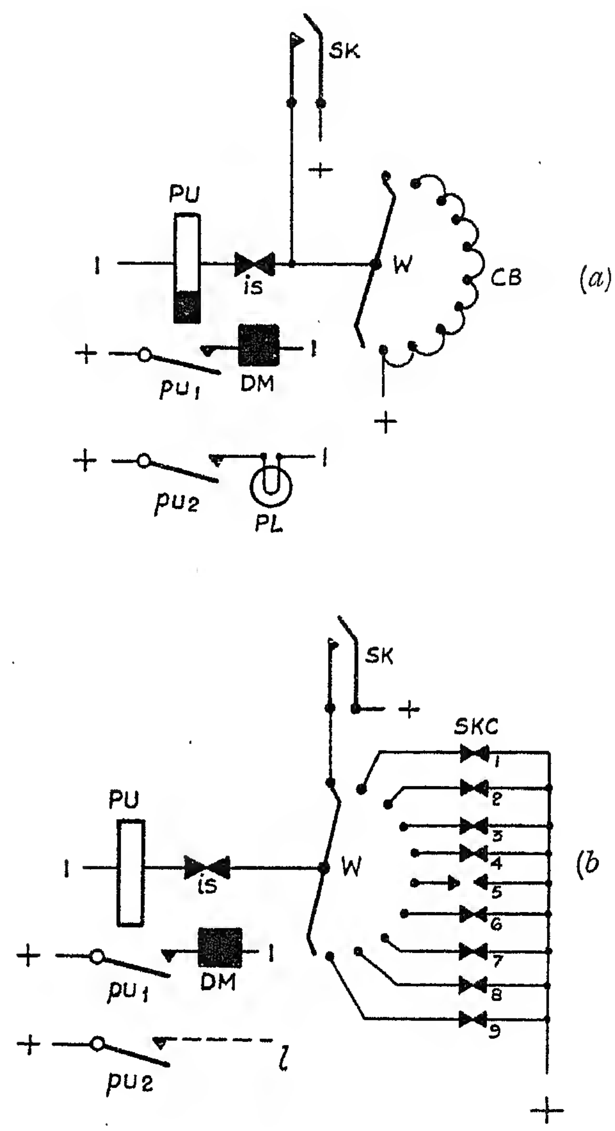


Fig. 12

wiper W through the interrupter springs *is* of the driving magnet DM. When the start key SK is operated, relay PU is energized over the circuit positive, *is*, windings of PU, to negative. PU at pu_1 closes a circuit for DM which energizes but does not step wiper W at this stage. When DM is fully energized, it opens its springs *is* (see Fig. 6) and relay PU releases after a short pause. The release of PU de-energizes DM, and wiper W makes one step. The circuit for PU is now made via the bank CB of the switch, and PU and DM interact with one another to produce a continuous stepping action of the switch. At the end of the revolution the switch will come to rest if SK has been released in the meantime. If not, the switch will step indefinitely until SK is restored. At contacts pu_2 relay PU flashes a pulse-indicating lamp PL.

In practice, what is actually desired is to make the wiper W move to a definite contact in the bank CB and to send out pulses corresponding to this position which will impulse a similar switch at a remote point and place its wiper or wipers on the corresponding contact [see Fig. 12(*b*)]. Referring to this figure, the positive " marking " on the bank contacts is led through a series of selecting keys SKC. When one of these keys is thrown, it removes positive from the contact to which it is connected. On operating the start key SK, the operation is exactly the same as that previously described. When the wiper W reaches the bank contact from which the positive marking has been removed, the eircuit for the pulsing relay PU from negative via *is*, W, and the bank contact to positive, is broken, pulsing stops, and the switch wiper remains standing on the unmarked contaet (contact 5 in the diagram). Five pulses will have been sent out to the distant switch via contact pu_2 and line 1, and if these have been correetly received both switches will stand on their fifth contacts.

Switch-position-checking Methods

As the object of positioning a remotely situated switch in the manner just deseribed may be the selection of one of the number of circuit breakers and its subsequent tripping or closing, it is obviously of the utmost importance that the correct position of the selector switch be tested and indicated before the tripping or closing operations are performed.

The correct reception of a signal train might possibly be interfered with by external disturbance, and there are two methods of testing which are widely used.

(1) The revertive impulse method is one in which each pulse sent out from the transmitting station is answered by the receiving station before the next pulse is transmitted.

(2) In the impulse-counting method, the signal train consists of an invariable number of pulses in two groups, one positive, the other negative. The total number of the two groups is constant, but their individual number will alter according to the selection which is to be made and their effect is to set up a checking and confirming circuit as soon as the total train has been transmitted for the purpose of signalling to the control operator that he can proceed.

Fig. 13 illustrates a method of accomplishing the revertive impulse system of checking.

When start key SK is operated at the control station, driving magnet DM is energized from positive, ons-1, SK, first contact of CB, wiper W, winding of DM to negative. When SK is released, wiper W moves on to the second bank contact and DM is now placed in series with the impulsing relay IMP via contaet ons-2 (now made), *is*, co-1 of relay CO, winding of IMP to positive. DM does not operate in this circuit but IMP does and at imp-1 closes a circuit for relay CO in series with DM. At imp-2 and imp-3 battery is applied to lines L1 and L2, and relay A at the substation is thereby operated. A at its contacts a1 closes a circuit to DM via the first contact of bank RS-2 of the rotary switch and DM energizes in readiness to move the two wipers W1 and W2 off-normal. A at its contacts a2 closes a circuit for relay IRL, which operates and at its contaets irl 1 completes the circuit for relay M via wiper W1 and first bank contact of RS-1.

At the control station relay IMP did not release immediately its circuit was broken by relay COd/R, due to the holding-on effect of its copper slug, but after a time sufficiently long to operate relay A reliably at the substation, the pulse is terminated. DM at the substation also releases and wipers W1 and W2 take one step to their next bank contacts. As a result of this a circuit is now closed for relay N via second bank contact of RS-1 and

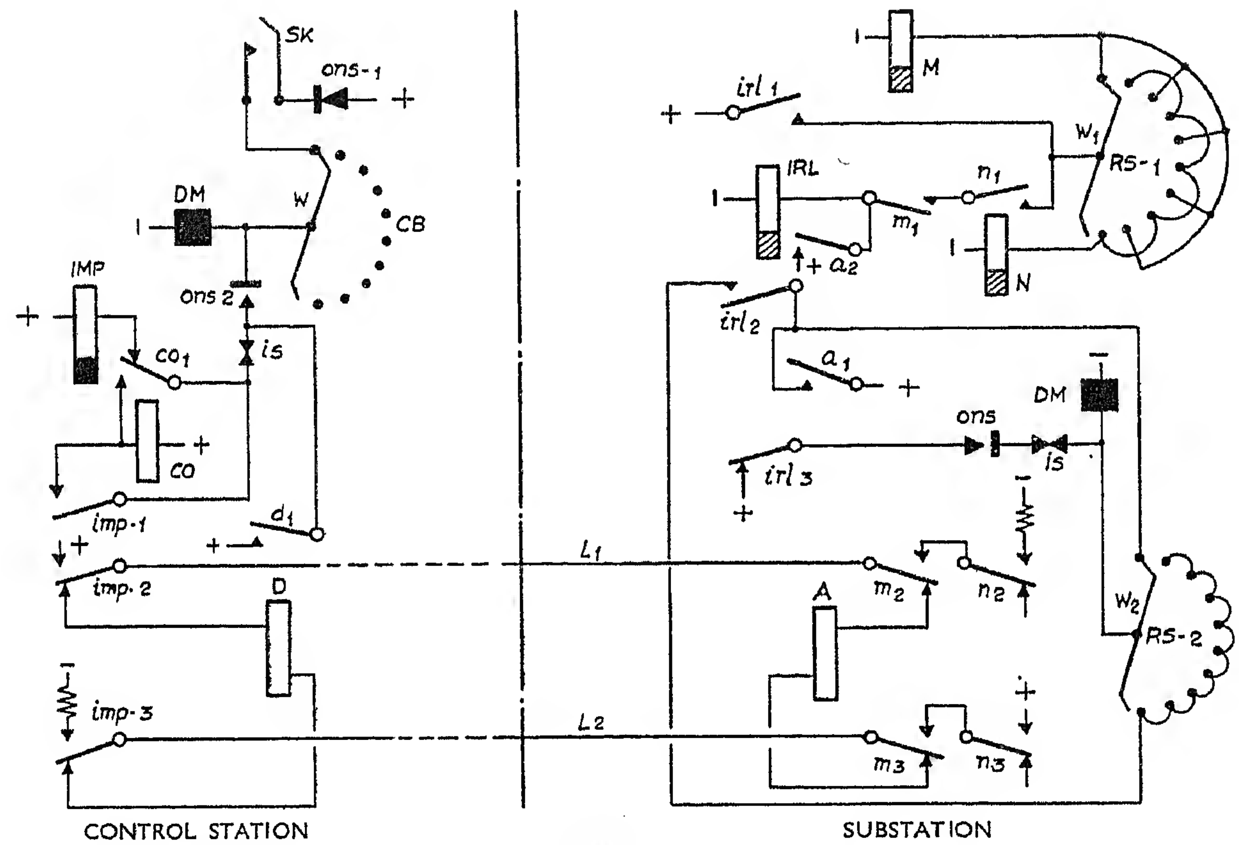


Fig. 13

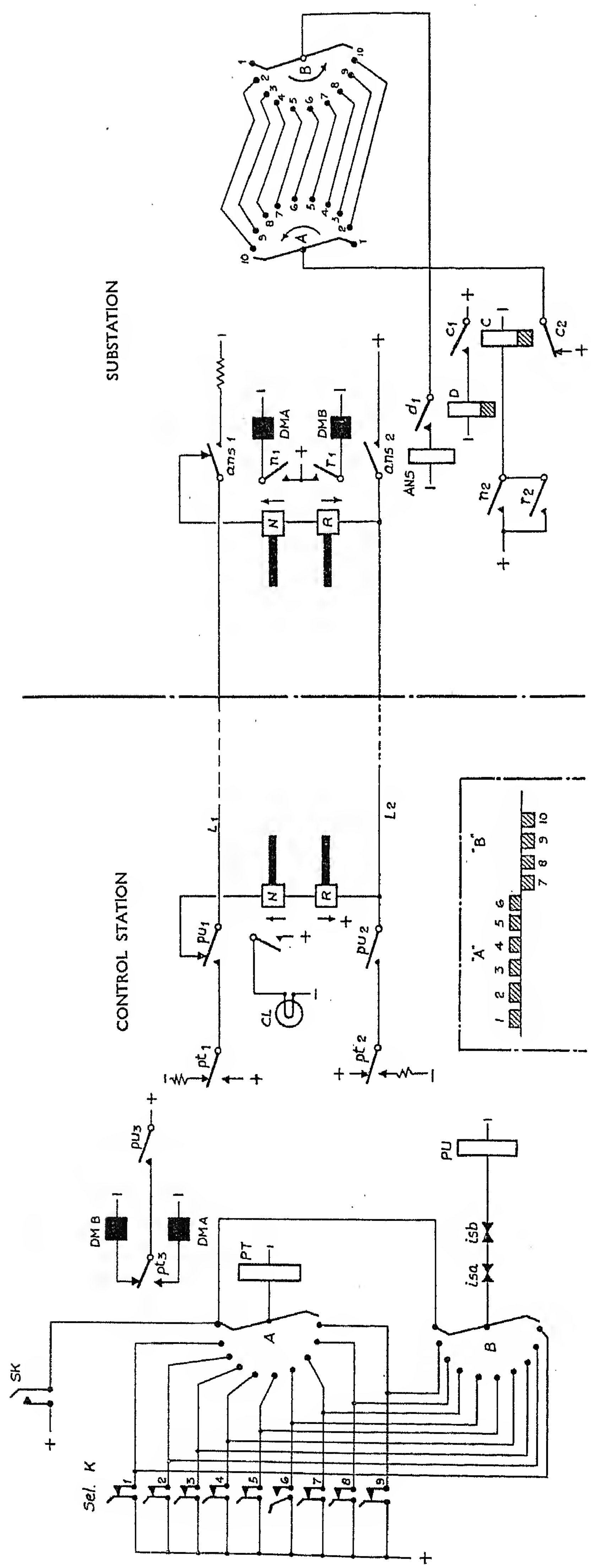


Fig. 14

contact irl 1. Owing to the slug on relay M, this holds up for a certain time and there is an overlap of the operating times of relays M and N. As a result, a battery pulse is applied to the lines L1 and L2 via contacts m2, n2, m3, n3, and relay D at the control station is operated. This constitutes the "answer back" signal. Relay D at contacts d1 pulses DM so that the switch takes a further step and short-circuits CO via *is* and operated contact CO_1. CO releases, re-inserting relay IMP in its previous circuit in readiness to send the next pulse to the substation. When D releases, relay IMP at once becomes operative and another pulse is sent from the control station to the substation, thus stepping the wipers W1, W2, there to the next bank contact.

This to-and-fro exchange of impulses constitutes a check on the position of the two switches, since the cyclic interchange cannot proceed unless the two step regularly. The "revertive impulse" system is quicker for a small number of selections (up to 10), but the "impulse counting" method is simpler and saves time in the case of a system with a large number of points. With such a system, in conjunction with the two-motion Strowger selector mechanism, any one of 1 000 points can be selected and checked in less than 4 seconds.

Fig. 14 explains the principles of the impulse counting method. At the control station, two switches A and B are provided. When a selector key Sel.K has been thrown and the start key SK is operated, relay PT operates and at contacts pt3 removes the driving magnet DMB of switch B from the pulsing circuit to be described later and inserts the driving magnet DMA of switch A in this circuit.

At contacts pt1 and pt2 the line battery is reversed so that the pulses now to be sent out are of a certain polarity. Pulse relay PU is also operated by SK via the first bank contact of switch B and interrupter springs *isa* and *isb*. PU at its contacts pu3 closes the circuit for driving magnet DMA and at its contacts pu1 and pu2 disconnects the lines L1 and L2 from polarized relays N and R and connects them to contacts pt1 and pt2 now in the operated position. A pulse passes out to line in such a direction as to operate relay N at the substation, which closes a pulse circuit for driving magnet DMA there. At the control station DMA, when fully energized, opens its interrupter springs *isa*, thus breaking down the circuit of pulsing relay PU. Switch A at the control station then makes its first step off-normal and the release of PU terminates the line pulse so that switch A at the substation also makes one step. The two switches continue to step together in the manner described until switch A at the control station reaches its seventh contact, where the selecting key Sel.K6 has been thrown. A circuit no longer exists for PT which, at its contact pt3, transfers the pulsing circuit from DMA to DMB and switch A remains on its seventh contact for the remainder of the cycle. The release of relay PT reverses at contacts pt1 and pt2 the direction of current applied to the line when the pulse relay operates, and further pulses are only effective to operate switches B at both stations. Pulsing relay PU now operates via the first contact of switch B over the circuit previously traced, and by its inter-action with DMB continues to pulse over the line to the distant station. The bank

contacts of switch B at the control station are connected to the keys Sel.K in reverse order to those of switch A and, when B has taken four steps, its wiper stands on its bank contact which is connected to Sel.k6 and the circuit for PU is thus broken down.

Switch A has thus taken six of its possible steps and switch B four, the number of steps complementary to six. The first six steps resulted in positive pulses to line, and the last four produced negative pulses, as shown in the inset diagram to Fig. 14.

At the substation switch A rests on its seventh and switch B on its fifth bank contact as the result of six and four steps respectively, and the wipers of the two switches are connected to one another through the bank wire connecting contacts 7 of A and 5 of B.

The intermittent operation of relays N and R at the substation pulsed a slow-to-release relay C which holds

The capacity of the switches would be at least 25 points, 10 having been taken for simplicity only.

Signal Train Testing from the Substation (Fig. 15)

When circuit breakers or tap-change switches alter their positions, the new positions are immediately signalled to the control station. At every such change the transmitting switch at the substation goes through a whole cycle, not only indicating any changes but also confirming the position as indicated of the remainder of the circuit breakers and transformer tap switches.

The receiving distributing switch at the control station should, if it keeps in step with the distant transmitter, go through a complete cycle also. If, owing to some outside interference, the distributor switch has not completed its cycle when the signal train ends, automatic means are provided for securing a repetition of the

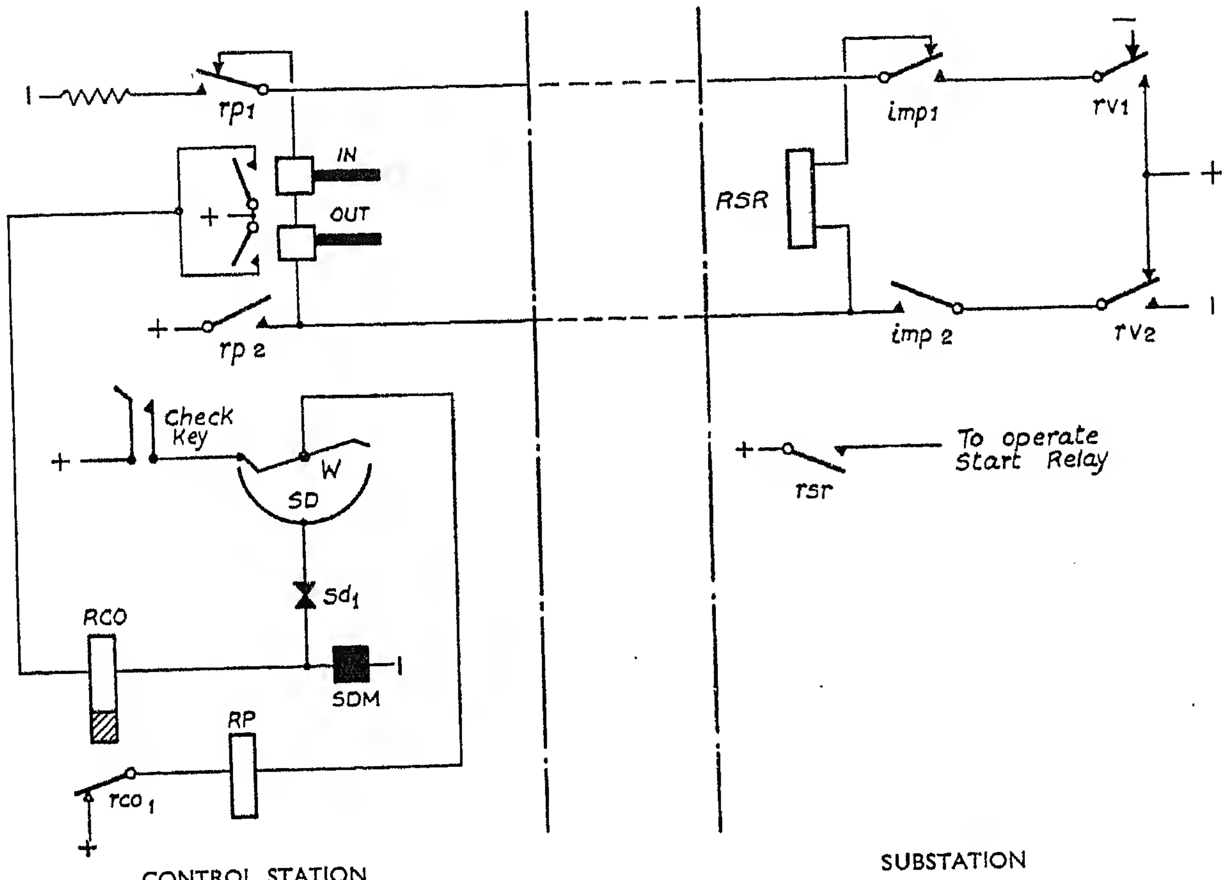


Fig. 15

up continuously during the receipt of the signal train. C in turn operates another slow relay D which at its contacts d1 prepares a circuit for an answer-back relay ANS. At the end of the signal train relay C releases, and a little later relay D, but before D releases, a circuit is closed for ANS from negative, winding of ANS, operated contact of d1 of D, wiper of switch B, bank contact 5 of B, wire to contact 7 of A, wiper of A, released contact c2 to positive. ANS energizes in response and at its contacts ans1 and ans2 applies battery to the line after disconnecting relays N and R. At the control station relay N operates as a result of the answer-back pulse, and lamp CL lights, indicating to the control operator that the selection has been correctly made. It will be seen that unless the total impulses of the train have been correctly received, and also the correct number of positive and negative pulses recorded, the checking signal cannot be transmitted.

transmission from the substation. The " in " or " out " position of a circuit breaker is indicated by positive or negative currents which operate the polarized relays IN and OUT at the control station. The total pulses will be constant and some of them may be negative, but each pulse, positive or negative, operates driving magnet SDM in series with slow-to-release relay RCO. If the impulse train is correctly received at the control station, switch SD will be normal at its completion, as shown in the diagram. If, however, impulses are lost in transmission, wiper W will be off-normal and making contact with the continuous segment corresponding to 24 of the 25 points of SD. Relay RCO releases and at its contacts rco1 closes a circuit from positive, rco1, winding of repeat relay RP, wiper W, bank segment of SD, sd1, SDM to negative. The switch rapidly returns to the normal position, relay RP also operating and at its contacts rp1 and rp2 applies battery to the line which

operates a re-starting relay RSR at the substation. RSR completes a start circuit for the sending switch there and the indications are repeated.

If the control operator wishes at any time to confirm

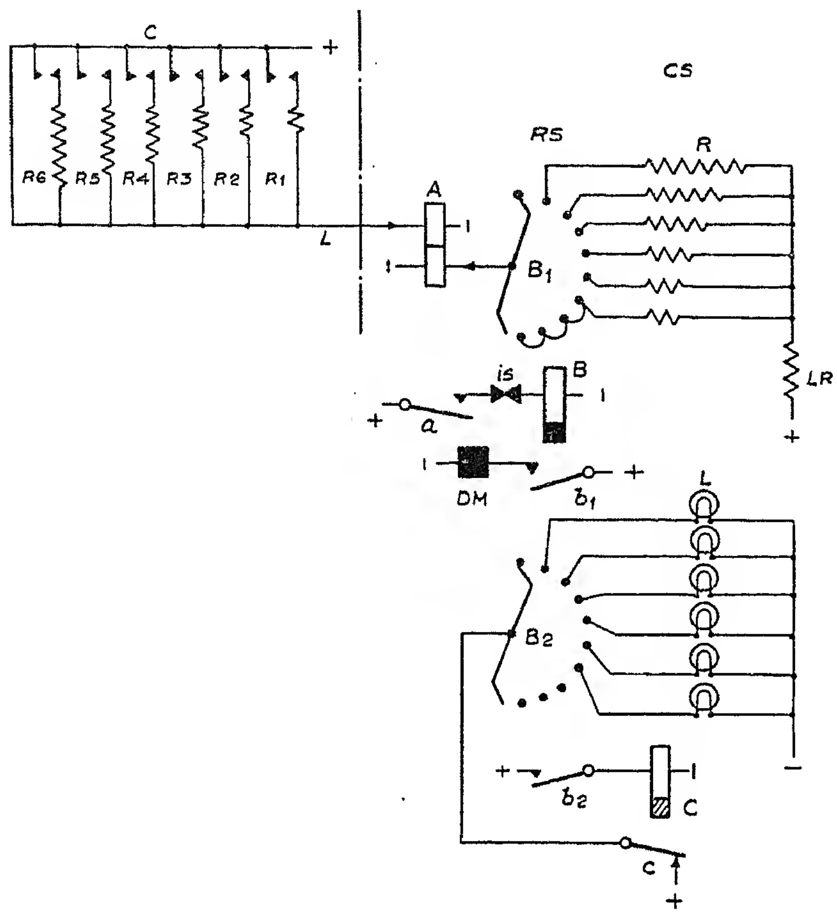


Fig. 16

the indications displayed on the board, he has only to operate the check key and RP will act as described in connection with the automatic repetition of faulty reception.

(5) THE TRANSLATION OF METER AND OTHER INDICATIONS INTO SIGNAL TRAINS

The basis of the methods of remote supervisory control dealt with in this paper is the use of impulse trains generated under the control of uniselectors (rotary switches) of the type used in automatic telephony.

It is clear that if we have some means of generating trains of impulses the length of which is proportional to the deflection of an indicating pointer, then, whatever the quantity to be indicated, electrical or mechanical, it is only necessary to employ as a receiver a uniselector provided with a pointer moving over a suitably marked scale and the translation of the signal train into an indication is accomplished.

Fig. 16 shows a method of recording at a central point such matters as the water-level in a reservoir or the position of sluice gates at some place remote from the observing centre. At the transmitting point a number of contacts C are so arranged with respect to the mechanism to be observed that any one of these contacts may be closed. Their closure applies to the line L current which, at the indicating station, operates relay A. At its contact relay A closes a circuit for relay B through the interrupter springs *is* of the driving magnet DM of rotary switch RS. The interaction of B and DM steps the switch RS from contact to contact.

At its second contact b2, relay B pulses a slow-to-release relay C which remains energized during the pulses. When the wiper of the upper bank B1 reaches the contact on which a resistance R equals in value the resistance inserted in the line circuit at the transmitting point, relay A is traversed by equal currents in opposite directions and de-energizes, thus stopping the stepping of the switch. After a pause, relay C releases and closes at its contact c, a circuit from positive, c, wiper B2, contact on which wiper is resting, and the indicator lamp connected to that contact, negative.

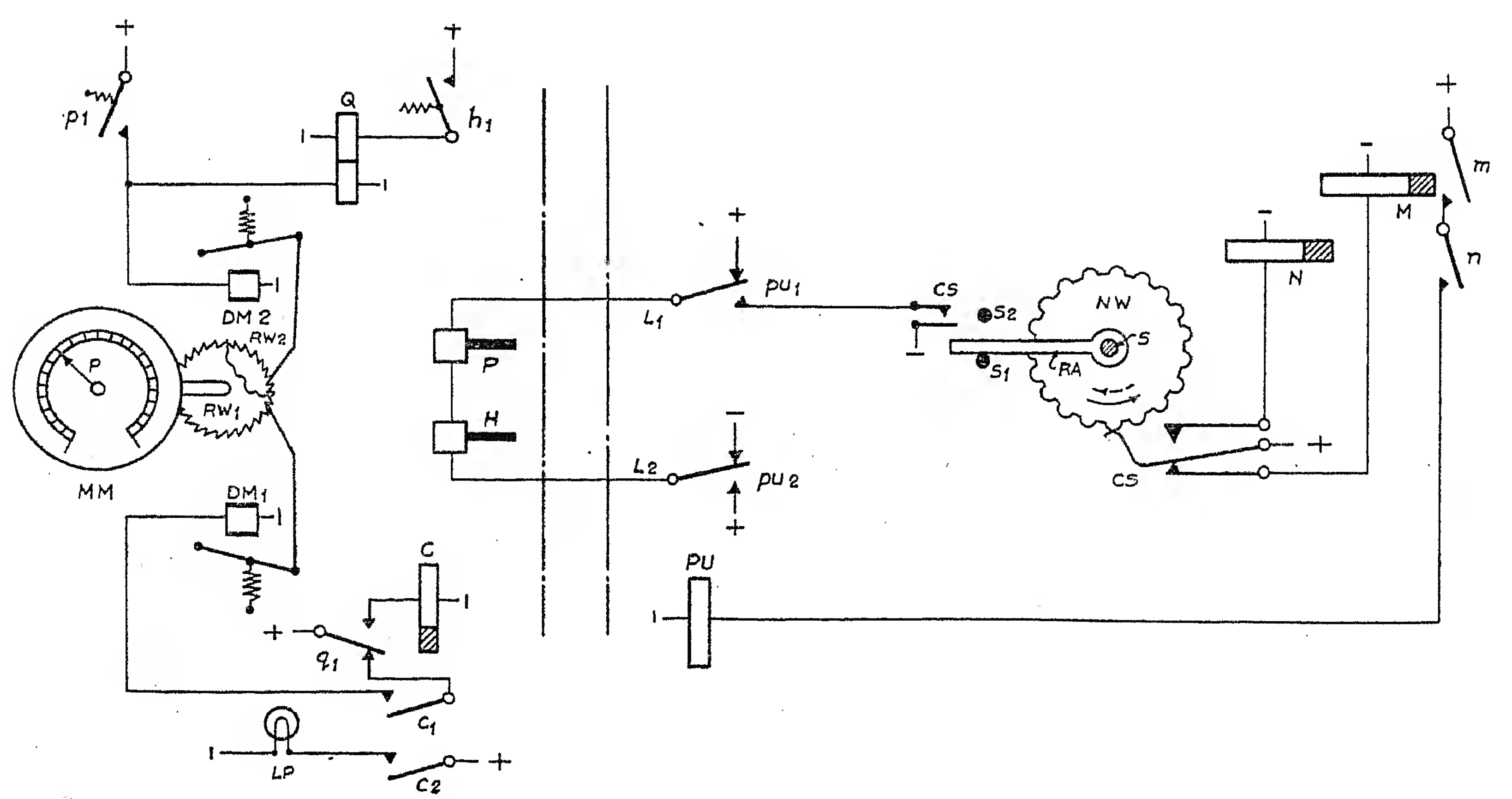


Fig. 17

The lamps L may illuminate a scale suitably graduated. The resistance LR is in series with all the resistances R to balance the line resistance and thus secure that when the two resistance paths in series with the upper and lower windings of the relay R are identical, the flux resulting in the core is zero.

In this case the pulsing is not transmitted from the mechanism whose condition is to be indicated, but is generated locally at the indicating point.

Fig. 17 shows a method in which changes in the angular position of a shaft S is indicated at a central station. S may be the shaft of a water-level indicator, rotating in either direction as the level of the water rises or falls. The transmitter consists of a notched wheel NW mounted rigidly on S and depressing and releasing a contact spring CS which makes contact alternately with two other springs and so energizes in turn two relays M and N which are slow to release. Due to the slow-to-release feature of M and N there will be an overlap period during which their contacts m and n will be simultaneously closed, and when this occurs pulsing relay PU will operate.

Friction-tight on S is a reversing arm RA which is carried round with S when the latter rotates in a clockwise direction and closes two contact springs CS. The motion of RA is limited by two stops S1 and S2. If S rotates counter-clockwise, RA remains on stop S1 and is ineffective. At the receiving end two reversely mounted ratchet wheels RW1 and RW2 are mounted on a shaft which carries a pointer moving over a graduated scale. The pointer will be moved clockwise or counter-clockwise, according to which driving magnet, DM1 or DM2, is pulsed. With the system at rest, as shown in the diagram, relay H is operated and at its contact h1 closes a circuit for relay Q. Q at q1 operates relay C which at c1 partially completes a circuit for DM1 and at c2 closes a circuit for a pilot lamp LP.

If the notched wheel NW should be moved in a counter-clockwise direction, the operation of relay PU is to break the line circuit since the springs CS at the transmitter are open. When relay PU is released relay H is re-operated. The alternate pulses and disconnections are followed by relay Q, and relay C holds continuously in the energized position so that on a line disconnection a circuit is closed to driving magnet DM1 from positive, q1, c1, winding of DM1 to negative. The pointer P of the mechanical meter MM is thus stepped round in a counter-clockwise direction proportionally to the movement of S. If S moves in a clockwise direction the springs CS are closed and the direction of the current pulses is now reversed while the interval between pulses is represented by currents of the normal sign. Thus relays P and H operate alternately, P at p1 closing the circuit to DM2, while either p1 and h1 energizes relay Q, keeping this in the operated condition. Q at q1 keeps relay C energized and disconnects the circuit of DM1.

The notched wheel with its contact springs CS, reversing arm RA, and 2 slow-to-release relays M and N, is very generally used to translate positive or negative angular movements into a coded pulse train.

Fig. 18 is a method of translating meter readings into pulse trains which is based on the well-known Midworth repeater. OM is the originating movement mounted on a shaft S1. It carries at its lower end a metallic tongue T, which plays between a fork F carrying two contacts mounted on a second shaft S2, independent of, but co-axial with, S1. S2 is geared to a motor M mounted on a shaft S3 which carries a notched impulsing wheel IW and a friction-tight reversing arm RA. If the originating movement moves in either direction, T makes contact with one or other arms of the fork and a circuit is closed for one of the two field windings F1,

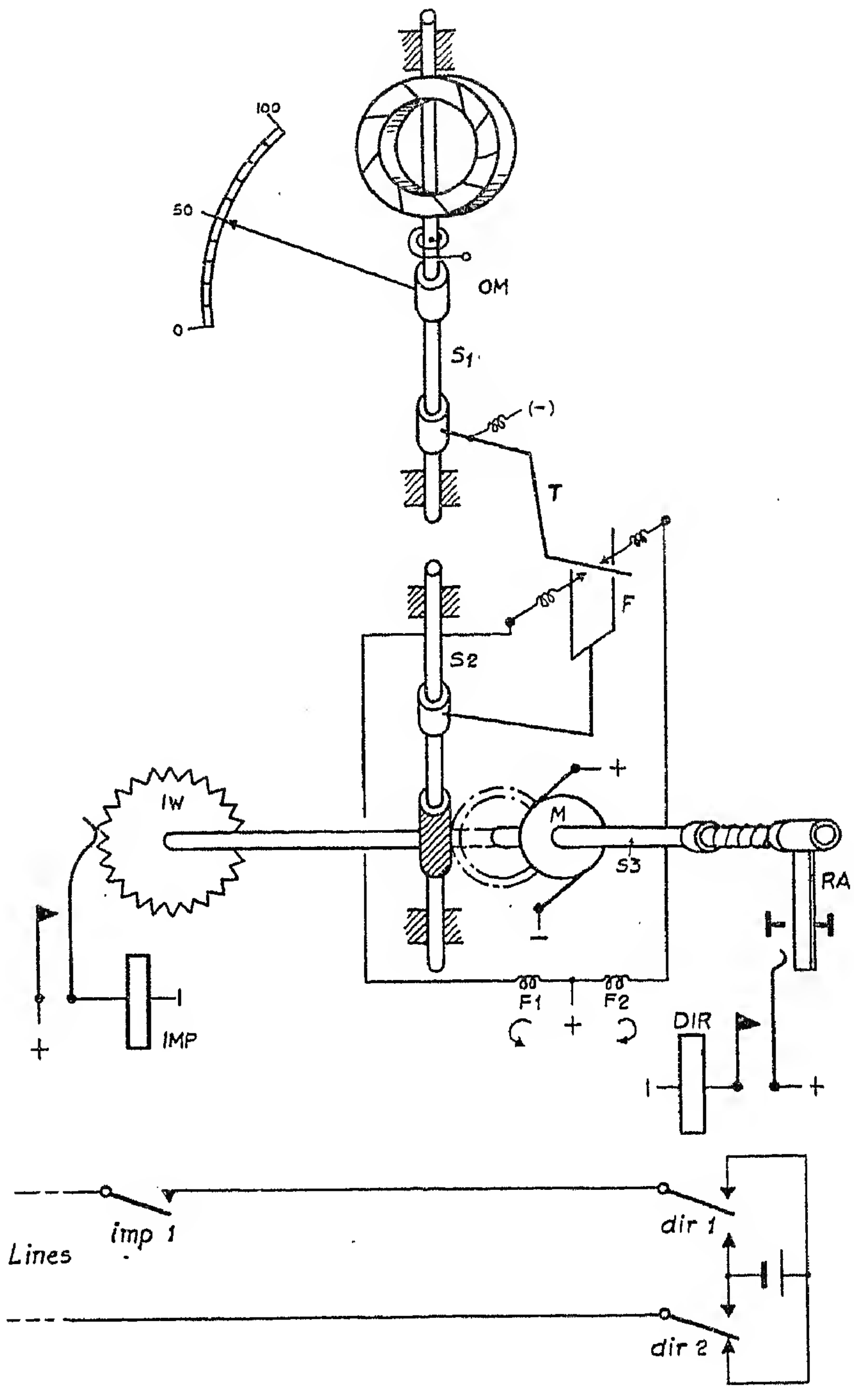


Fig. 18

F2, of motor M which is driven so that the fork tends to free itself from contact with the tongue T. When this is effected, F has moved an angular distance represented by the displacement of the originating movement to its new position, and a corresponding train of impulses is sent to the distant indicating station. These pulses position a mechanical meter of the type described in connection with the last figure. The pulses are either positive or negative, according to the direction of rotation of IW and the influence of RA on the direction relay DIR.

Fig. 19 represents a method of intermittently indicating the position of a measuring instrument which is based on a principle analogous to the thread recorder.

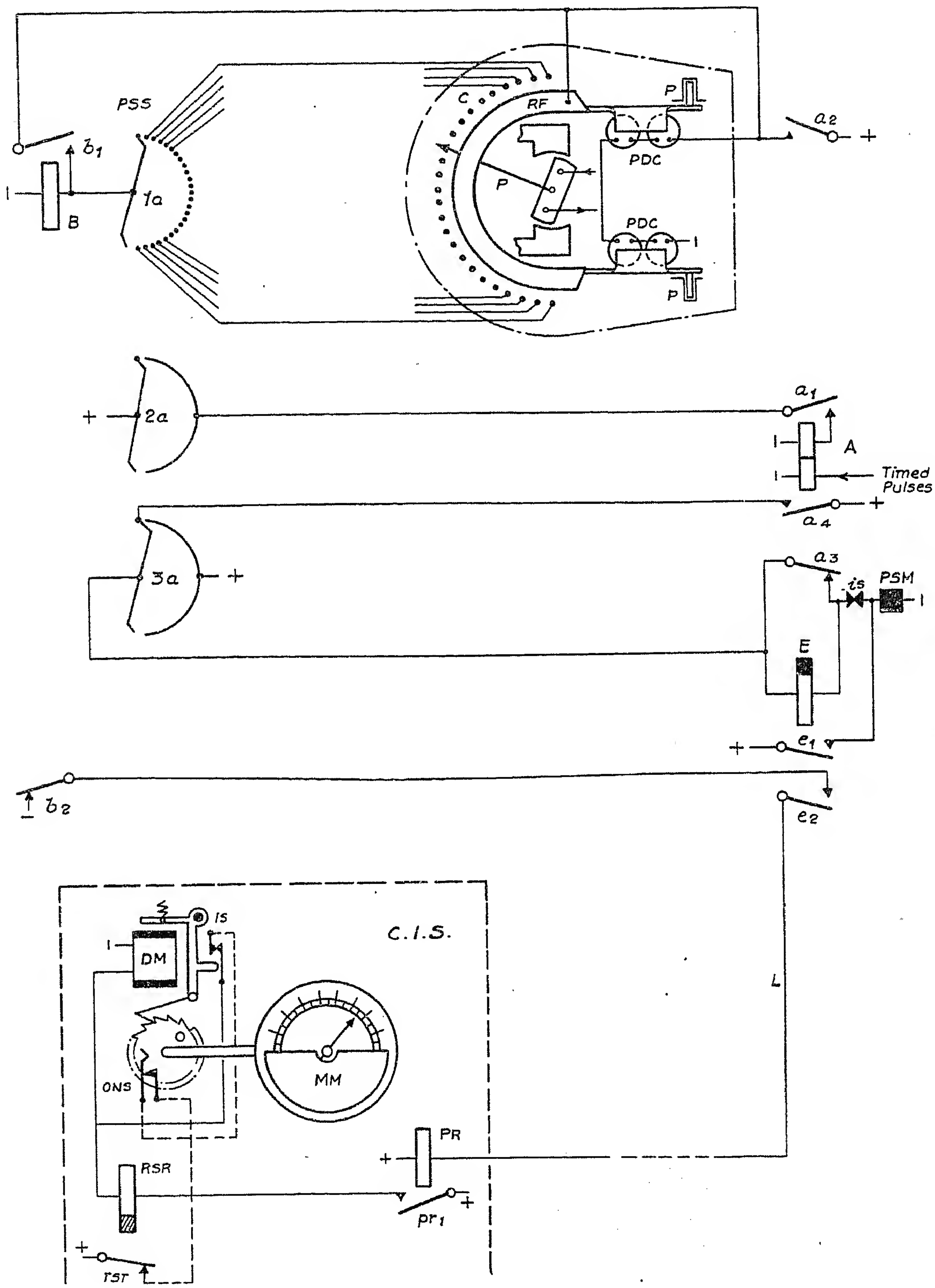


Fig. 19

The pointer P of the measuring apparatus plays freely over a circular row of contacts C and under a semicircular rocking frame RF which, when operated, clamps pointer P to the contact C opposite to which it is at that moment placed. RF is held free from P by springs not shown and is pivoted at P, P. It is operated to clamp P each time its pair of pull-down coils PDC are energized, and this is effected by pulses sent at regular intervals which operate relay A.

The operation of the arrangement is as follows:—A is operated over its lower winding and prepares a locking

circuit for itself at contact a1. At a2 it completes a circuit for the pull-down coils PDC and at a3 removes a short-circuit from the impulsing relay E. At a4 it completes a circuit via first bank contact and wiper 3a of pulse-sending switch PSS and relay E in series with the driving magnet PSM of the switch. Relay E alone operates in this circuit and at e1 completes an energizing circuit for magnet PSM and at the same time short-circuits itself. Owing to its copper slug, E remains energized sufficiently long to ensure full energization of the driving magnet. The magnet opens its interrupter springs, *is*, releasing relay E, on the occurrence of which the circuit of the driving magnet is broken; it releases, and advances the wipers 1a to 3a into engagement with the next set of bank contacts. In this position wiper 2a engages the common plate maintaining a holding circuit for relay A independently of the pulsing circuit, while wiper 3a engages a common plate to maintain the driving circuit for PSM. Accordingly the wipers of the pulse-sending switch are automatically rotated over their bank contacts and at contact e2 of relay E a circuit is intermittently completed for the impulsing relay PR in the distant station, since E is operated and released for each step of the pulse-sending switch.

Owing to the energization of the pull-down coils PDC, the pointer P will be depressed into engagement with the contact stud corresponding to the reading obtaining at this time. The studs are wired to contacts in bank 1a of PSS, and the impulsing circuit to the distant station will be maintained until wiper 1a encounters the marked bank contact. Relay B now operates from negative, winding of B, 1a and bank contact, pointer P, frame RF, a2, to positive. Relay B operates and locks up at its contact b1, and at b2 opens the impulsing circuit to the distant station so that no further pulses are transmitted to the distant recorder after the marked bank contact is reached.

The operation of the impulsing relay PR at the distant station steps the indicator MM, which thus takes up a position corresponding to the reading of the initiating meter. This indicator may be so arranged that its return to the normal position is effected a short time after each reading has been made.

Returning to the transmitting end, the wipers continue their automatic rotation until the home position is reached, whereupon wipers 2a and 3a no longer connect with their common plate and thus the circuits of relays A and E are opened. On releasing, A opens the circuit of PDC, freeing the meter pointer P which will take up a position in accordance with the supply to which it is connected. The holding circuit for relay B is broken and conditions are restored to normal.

The automatic return to normal of the mechanical meter MM at the indicating station is accomplished in the following manner. In series with DM is a low-resistance relay RSR which remains in the energized position during the receipt of a pulse train. When the train is ended, relay RSR releases after a pause and closes a self-driving circuit for the meter MM from positive, rsr, ONS, *is*, winding of DM to negative. DM energizes over this circuit and when fully energized opens its own circuit at the interrupter springs *is*. This continues until the normal position is reached, when the circuit just traced is broken down at the off-normal springs ONS.

A method has recently been developed by the Automatic Electric Co. for the remote indication of power-station meter readings in which the transmitter observes, by optical means, the deflection of the instrument and converts these into easily transmitted electrical currents. These currents are received on a moving-coil instrument scaled to correspond to the transmitting instrument.

The transmitted currents have a time element which changes with the meter reading, and the receiver is made to depend upon this time element and be independent (within wide limits) of the magnitude of the received currents. Thus attenuation in the transmitting line has little influence on the meter reading.

Fig. 20 shows diagrammatically the mechanics of the transmitter. MV is a semicircular vane attached to the rear end of the instrument shaft and arranged to uncover a mirror M when the instrument is deflected from zero. Between the mirror and the vane is a toothed disc TD. Light from an under-run gas-filled lamp L passes through a lens Z, is deflected by a prism P, falls on mirror M and is then reflected on to disc TD. The lens is arranged to focus the filament of the lamp on to the back of TD, where the image formed is very narrow and capable of being absorbed by the back of one tooth of TD. The lens and prism rotate continually at about 100 r.p.m., and when the light reflected from M falls between two teeth there is a flash of illumination on the photo-electric cell PC. The disc has a large number of slots so that the flashes of illumination occur at any desired voice frequencies, say 300 to 3 000 flashes per second.

When the instrument is reading full-scale, the whole of the semicircular mirror is uncovered and the flashes of light on the cell are continuous, for as soon as one spot of light reaches the end of the mirror another spot produced by the diametrically opposite lens reaches the beginning. When the instrument is reading half-scale, the vane covers half of the mirror and flashes occur for a certain period of time, followed by darkness for the same period. When the instrument is reading zero, no light reaches the cell.

The currents in the photo cell corresponding to these three instrument readings are shown in the lower part of the figure. After the photo-cell currents have been amplified to a convenient level for transmission they take the form of a 100 per cent modulated carrier.

The transmitting device is approximately 10 in. dia. and fastens on the back of the sending instrument.

The receiving instrument contains a rectifier for converting the modulated carrier back to d.c. impulses. These impulses are fed into a well damped moving-coil instrument which reads the mean value of the current flowing. By arranging that a continuous current gives a full-scale reading, the deflection of the receiving instrument is made to correspond to that of the transmitting instrument.

Since the deflection of the receiving instrument is dependent upon the magnitude of the voltage (local) as well as upon the time ratio of the impulses, special precautions are taken to keep this voltage constant. The voltage of the supply to the instrument is maintained within

very close limits, and the resistances in series with the instrument are kept sensibly constant. A valve anode circuit forms part of the series resistance, and to avoid variations in anode current it is arranged, firstly, that the grid of this valve is swung heavily by the incoming signal, making the impedance of the valve fairly constant for varying signal strengths, and secondly that the valve impedance is negligibly small compared with the fixed resistance, which forms the major part of the circuit impedance.

A 3-electrode neon tube is employed for applying a heavy positive bias to the grid of the rectifier. On weak signals, such as overhearing and induction from power lines, the neon tube does not strike and the rectifier is biased heavily negative. On normal signals the neon tube strikes and applies heavy positive bias to the rectifier. The accuracy of the reading is thus independent (within limits) of background noises and attenuation in the line.

At the control desk the telegraph head is common to a number of control lines, any one of which may be selected by the operation of a selecting key. The line so selected is then connected to telegraph equipment at both its terminals.

The main outlines of such an arrangement are set out in Fig. 21. To send an instruction the control engineer rotates the instruction dial ID to the instruction required and then operates the selecting key SK which, by means not shown, selects the line to the station to which the instruction is to be transmitted. A contact on SK via first bank contact and wiper of switch A operates relay PT. The same circuit also operates, in a parallel path, via first bank contact and wiper of switch B and interrupter springs of driving magnets ADM and BDM, the relay PU. PU in operating disconnects at pu1 line L1 from the two polarized relays N and R and extends the latter to contact pt2. Contact

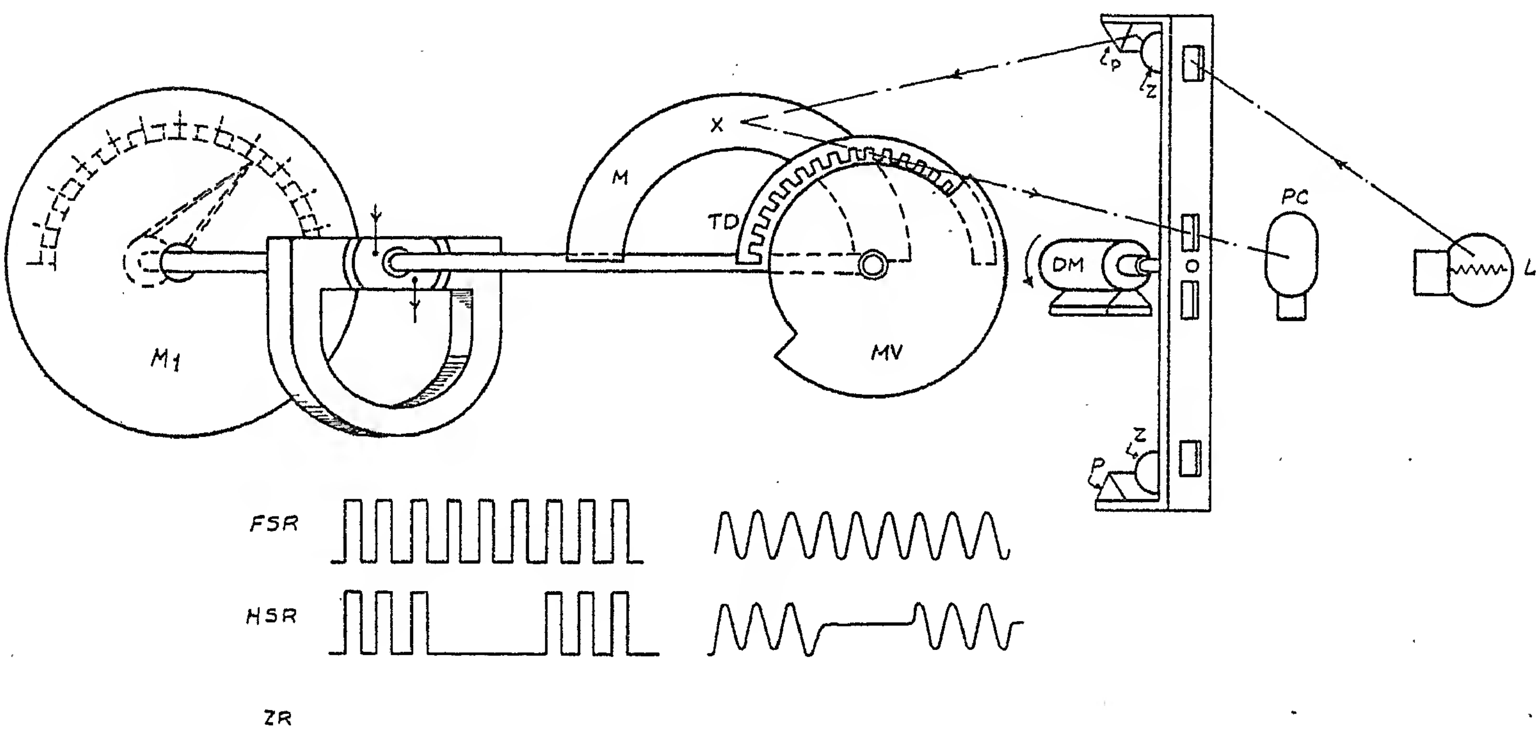


Fig. 20

pu2 extends line L2 to contact pt3. PT in operating reverses the voltage now applied to lines L1 and L2 from pt2 and pt3. PT at pt1 disconnects driving magnet BDM and connects driving magnet ADM in the pulsing circuit completed by pu3. When ADM operates, it interrupts the circuit to relay PU, which releases, and switch A takes one step. This interaction of ADM and PU continues until the wiper A1 of switch A encounters its bank contact connected to the set of contact springs in the instruction dial ID, which have been opened by the action of the control operator in setting the instruction dial. The train of pulses so far generated are transmitted to the distant station where they operate the polarized relay N and through it the driving magnet A of switch A, which has three banks with corresponding wipers.

Relay PT releases when wiper A1 reaches the contact corresponding to the instruction being transmitted. The release of relay PT reverses the direction of the voltage applied to the line and disconnects the pulsing circuit from magnet ADM, switching it over to magnet BDM.

By suitably arranging the number of teeth in the slotted disc, any frequency in the audible band can be obtained. Several telemeters of different frequencies can be run simultaneously over the same pair of wires, and by employing frequencies above 2 000 cycles for telemeters and below 2 000 cycles for speech, meter readings and telephony can take place simultaneously.

(6) VISUAL INSTRUCTION INDICATORS

To obviate risk of misunderstanding, the more important operating instructions in frequent use are transmitted by a form of engine-room telegraph.

A typical set of stereotyped instructions is as follows:—

(1) Start-up.
(2) Shut-down.
(3) Raise kW.
(4) Lower kW.
(5) Stand by.
(6) Steady.
(7) Control.

Relay PU now interacts with this driving magnet, and pulses are transmitted over the line of opposite direction to those forming the first train. Switch B at the control room steps round until the pulsing circuit is again broken, which will occur when the wiper encounters the opened contact springs in the instruction dial. It will be noticed that the bank contacts of switch B are connected up in the reverse manner to those of switch A. Consequently switch B will take a number of steps represented by 8 minus the number of steps previously taken by switch A, and the train of impulses passing to line will, if, say, the fourth instruction is being transmitted, consist of 4 positive and 4 negative impulses. Whatever the ratio of the two sets of pulses, their total number always equals 8.

Assuming that instruction No. 4 has been transmitted, then at the substation, both switch A and switch B will have their wipers standing on their fifth bank contacts.

During the time that the impulses are being received at the substation, relay SR is maintained operated by pulses to the A and B magnets. On completion of the impulse train this relay restores to energize relay SEL from positive via sr1 contacts, A1 wiper on contact 5, B1 wiper on contact 5, SEL coil to negative.

Relay SEL now operates to disconnect the polarized relays N and R from the line and to complete a circuit for relay N at the control room, from positive via ans2 and sel2 contacts, L2 line, R and N coils, pu1 contact, L1 line, sel 1, and ans1 contacts, to negative. The condition of the circuit is now as follows:—

Relay N at the control room operates and connects a flicker circuit to the selected lamp via the A2 wiper on contact 5 of the A switch, to indicate that the selection is correctly set up. At the substation, signal lamp 4 is lit in series with an alarm bell AB from negative, bank contact 5, wiper A3, contact ans3 of relay ANS, and contact sr3 of relay SR, to positive.

The substation attendant now turns the pointer of

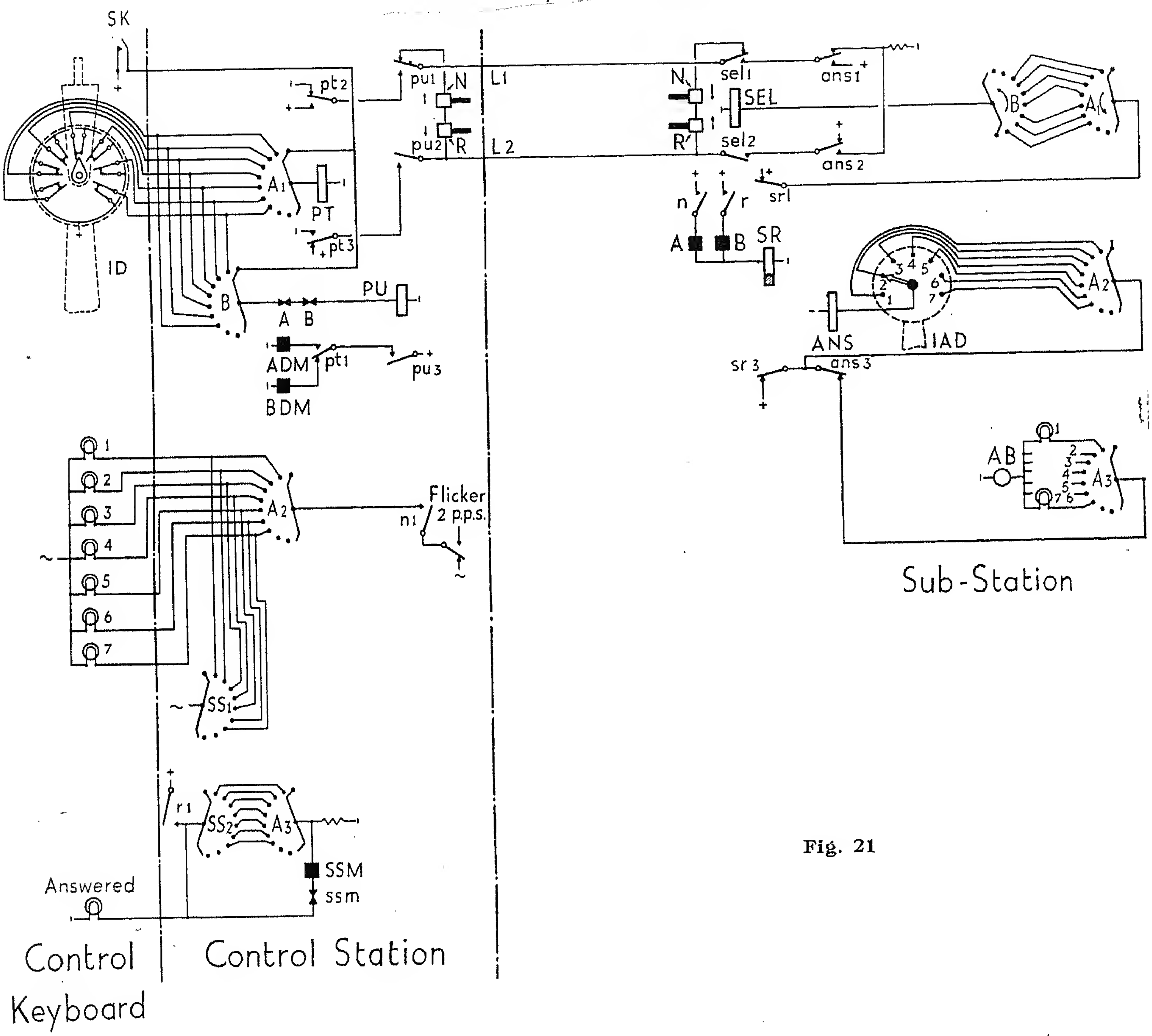


Fig. 21

his instruction dial to position 4 and this closes a circuit for the answering relay ANS from negative coil of relay ANS, pointer and contact 4 of IAD, bank contact 5 and wiper A2 of switch A, contacts of sr3 to positive.

Relay ANS operates and reverses the line current at its contacts ans1 and ans2 to cause relay N to release and relay R to operate at the control room.

The operation of relay R closes its contacts "r" to light the answered lamp and also causes the switch SS to rotate by completing a circuit via ssm and SSM and a resistance to negative. SS moves its wipers until the SS2 wiper rests on contact 5, whereupon the interrupter springs and the driving magnet ssm and SSM are short-circuited. SS1 now connects a steady supply to lamp 4 via its bank contact 5, to mask the flicker circuit and indicate to the control engineer by the steady glow of the lamp that the signal has been acknowledged.

The restoration of the start key SK causes switches A and B at both the control room and the substation to restore to normal by means not shown. The switch SS, however, remains in position to indicate the last signal sent to the substation.

(7) PROTECTION OVER SUPERVISORY CIRCUIT

It has been found possible to add to the supervisory equipment several forms of protection, chief among which must be mentioned the Longfield lock-in system and inter-tripping. The addition of lock-in protection gives rise to no special difficulties; all that is necessary is to provide between the stations some signalling channel which is not used for any other purpose. Since the impulse transmitted prevents the breaker from opening it is not necessary to take any abnormal precautions against false operation due to faults on the telephone line. It is of course essential that an alarm be given when the impulse is being received, so that the fault can be immediately cleared, or temporary arrangements made to give correct clearance in the event of a fault occurring on the power circuit.

The function of inter-tripping is to ensure that, in the event of any circuit breaker being tripped due to a line fault, the companion circuit breaker at the far end is tripped even if the protective equipment at the far end fails to operate for any reason.

The impulse sent along the telephone line for inter-tripping is very different from the lock-in impulse, in that it directly causes the breaker to open, and this under no circumstances may be imitated by any faulty condition which might give rise to extraneous current in the telephone line.

It is therefore essential that the inter-tripping signal should consist of a series of different impulses, forming a code of sufficient complexity to make operation by anything other than the correct sending device virtually impossible.

On d.c. systems the code consists of impulses of current following one another in rapid succession, some of them being of reversed polarity. The reception of the complete code without added impulses and with the reversals in the correct position is necessary for the operation of the tripping relay. With such an arrangement faulty operation due to line faults cannot occur, provided, of course, that alternate positive and negative pulses are not used, thus making the circuit sensitive to alternating current of low frequency.

Where the signalling channel is operated by voice-frequency currents a similar code is employed, but by employing several frequencies it is possible to transmit a single impulse of complex nature, and thus reduce the number of impulses required to produce a safe code.

Inter-tripping is in use between all stations in the South-West grid area, where all signalling is by means of voice frequency over Post Office lines. Three frequencies are used for the normal signalling, but only two frequencies are used at any one instant. It is thus evident that an impulse of all three frequencies provides a means of switching the equipment over from the indicating equipment to the protection circuits. This composite impulse is followed by three code impulses consisting of different combinations of two frequencies, and finally by all three frequencies simultaneously to trip the breaker.

The total time taken to close the tripping circuit at the far end is between $0\cdot8$ and $1\cdot5$ sec., and is independent of any signals which may be in progress on the line at the time at which the fault occurs.

(8) FUNDAMENTAL CIRCUITS OF REMOTE SUPERVISORY CONTROL INSTALLATIONS

Hardly any two installations are identical, owing to the variations in practical requirements, but there are certain main principles underlying them and Fig. 22 serves to illustrate how the selective functions of control and the automatic indication (supervision) of the condition of remote switches is effected over a pair of wires which may be a telephone pair.

Selection.

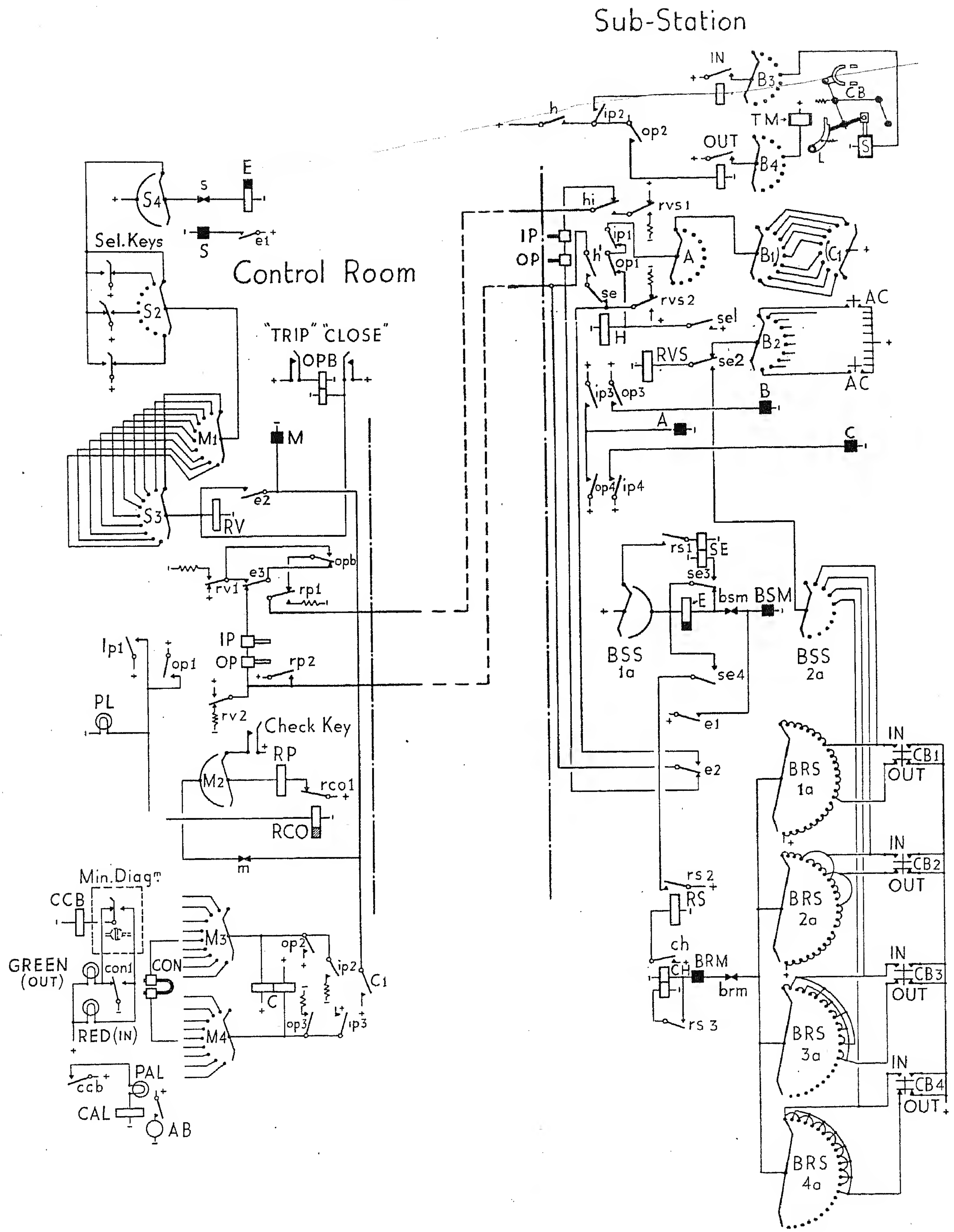
At the substation the closing and tripping magnets of each circuit breaker are selected through the wipers and contact banks B3 and B4 of switch B.

At the control room each breaker is represented by a selecting key, the operation of which causes a train of 10 impulses to be transmitted to the substation to select the circuit breaker corresponding to the key operated. It will be evident that trains of more than 10 impulses are used in cases where selectors having more than 10 contacts are used.

The train of impulses is divided into two groups, of normal and reversed polarity respectively, and switch B is stepped by the impulses in the first group. Unless the whole of the 10 impulses are correctly received, it is impossible to energize any circuit-breaker magnet and the equipment returns automatically to its normal condition. This safety feature makes it impossible to operate any circuit breaker other than the one corresponding to the selecting key which has been operated.

In the diagram only three of the selecting keys are shown, but the remainder are each connected to contacts in bank S2 of rotary switch S.

The impulses are generated and counted at the control room by the rotary switch S in conjunction with the relay E, which at its contact e3 repeats them to the substation. As switch S steps round one bank contact at each impulse, it will be evident that every impulse



Sub-Station
Control Room
Sel. Keys
"TRIP" "CLOSE"
OPB
Check Key
Min. Diagm
CCB
GREEN (OUT)
RED (IN)
CON
PAL
CAL
AB
PL
RCO
RP
RV
IP
OP
BSS 1a
BSS 2a
BRS 1a
BRS 2a
BRS 3a
BRS 4a
CB1
CB2
CB3
CB4
IN
OUT
TM
AC
BSM
BRM
RVS

Fig. 22

corresponds to a particular position of the switch and therefore to a particular selecting key.

The connections to bank S2 are such that the first contact is connected to positive supply whenever a selecting key is operated; all the other contacts of level S2, with the exception of the one corresponding to the operated key, which is disconnected by its operation, are normally connected to positive supply.

Assume that key No. 5 is in the operated position, as shown. This establishes a circuit for relay E via the home contact and wiper S4, interrupter springs *s*, and winding of relay E to negative.

Relay E operates and in turn energizes the operating magnet of rotary switch S, but E is immediately disconnected owing to the operation of the interrupter contacts *s*. When E releases, the operating magnet is de-energized, causing the switch S to step and re-establish the interrupter contacts *s*.

The actuation of a selecting key also completes a circuit to operate relay RV, via wipers S3, M1, and S2. When E operates, this circuit is extended to energize the magnet of switch M, which consequently steps in synchronism with switch S.

After relay E has been once energized to step rotary switch S, a circuit is established via the intermittently operated interrupter springs *s* and wiper S4 via the continuous bank, to cause S to proceed step by step for one complete sweep of its contacts.

Each impulse is transmitted to the substation by contact e3 of E. While relay RV is operated, the impulses will be of normal polarity, and this operated condition persists until wiper S2 reaches the contact connected to the operated selecting key, when the positive supply for relay RV is no longer available. Relay RV releases, causing the polarity of the impulse transmitted to the substation to be reversed. Also the circuit of the operating magnet M is disconnected, thus causing switches M and S to become out of step.

Relay RV and also switch M are not further operated during the selecting process, with the result that the remainder of the impulses transmitted over the line by relay E in conjunction with rotary switch S will be of reversed polarity.

At the substation the impulses are received by the polarized relays IP and OP, which respond to impulses of normal and reverse polarity respectively. Each relay impulses rotary switch B or C with which it is individually associated, while a third switch A is impulsed by both relays.

A total of 10 impulses will eventually have been sent out from the control station, of which the first 5 are positive in direction and the second group of 5 negative. If the impulses have been correctly received, switch A will have taken 10 steps, a complete cycle of operation, B will have taken 5 steps or half a cycle, and switch C 5 steps, also half a cycle. Thus the total train has been counted by switch A, and the two parts into which the train has been divided are counted by switches B and C.

A circuit is now completed from the check selection switch C1, via bank contact and wiper of switch B at B1, first bank contact and wiper of switch A, normal contacts ip1 and op1 of relays IP and OP to relay H, which operates in this circuit.

The operation of relay H causes current to be transmitted from the substation over the pilot wires to the control room, where it is received by one or other of the polarized line relays. These line relays are automatically connected across the line immediately the last impulse of the selecting train is transmitted.

The direction of the current transmitted from the substation by relay H, and therefore the particular line relay operated, will depend on the position of relay RVS. This will depend upon the position of the particular circuit-breaker auxiliary contacts to which it is connected by the wipers B2 of rotary switch B. This switch is now occupying a position corresponding to the breaker selected, consequently the polarity of the signal transmitted is determined by the position of this circuit breaker.

At the control room, switch M stands with all its wipers on their bank contacts representing the circuit breaker which has been selected. At wipers M3 and M4 a polarized relay CON controls the "in" and "out" signal lamps of the particular circuit breaker, so that when either relay IP or OP operates in response to the check back signal from the substation, not only is a pilot lamp PL lighted, indicating that the selecting process has been correctly performed, but the position of the circuit breaker, as indicated by its signal lamps, is confirmed.

Closing or Tripping of a Circuit Breaker.

The tripping of the circuit breaker CB is effected by energizing the trip magnet TM which, acting on the latch L, frees the linkage and allows the switch member to leave the fixed contacts. The breaker is put in the "in" position by actuation of the solenoid S, which rocks the linkage until the switch members are together, whereupon they are locked in this position by the latch L. TM and S are connected to contact No. 5 in the banks B3 and B4 of switch B. Either is selected by the operation of relay IN or relay OUT, and these are selected according to whether the operating pulse now transmitted from the control room is positive or negative. If the "trip" key is closed at the control room, relay OPB operates and at its contacts "opb" applies current to the line of a direction determined by the position of contacts rv1, rv2, of relay RV. This current operates the line relay OP at the substation to close the circuit of the OUT relay and this in turn operates the trip magnet TM.

If the "close" key is operated, relay RV is operated in parallel with relay OPB, and the direction of the line current is reversed, causing the IN relay to be operated at the substation.

Relay OPB, by means not shown, also causes the relays IP and OP at the substation to be replaced across the line in readiness to receive the current transmitted by OPB in this operated condition.

Automatic Indication of Circuit-breaker Positions.

For this purpose the circuit breakers are grouped in sets of 4 and their "in" and "out" contacts are connected to the 4 banks of a breaker-recording switch BRS. If a breaker changes its position, a circuit is completed from positive, the breaker auxiliary contact, bank and wiper of

the switch BRS, interrupter springs brm, driving magnet BRM, and upper winding of relay CH, to negative. BRM does not operate in this circuit but relay CH does and at its contact ch closes a circuit to relay RS which, in operating, closes a circuit for the lower winding of CH in parallel with its upper winding. The reduction in the resistance of CH brought about by this allows drive and locks up through its lower winding its contacts se3, se4, and rs2. The short-circuit on relay E is removed at se3 and positive supply is applied to E via operated contacts se4 and rs2. Negative supply is connected to E through drive magnet BSM, interrupter springs bsm, and winding of E, and this relay operates and at e1 closes an impulse circuit to drive magnet BSM. At the

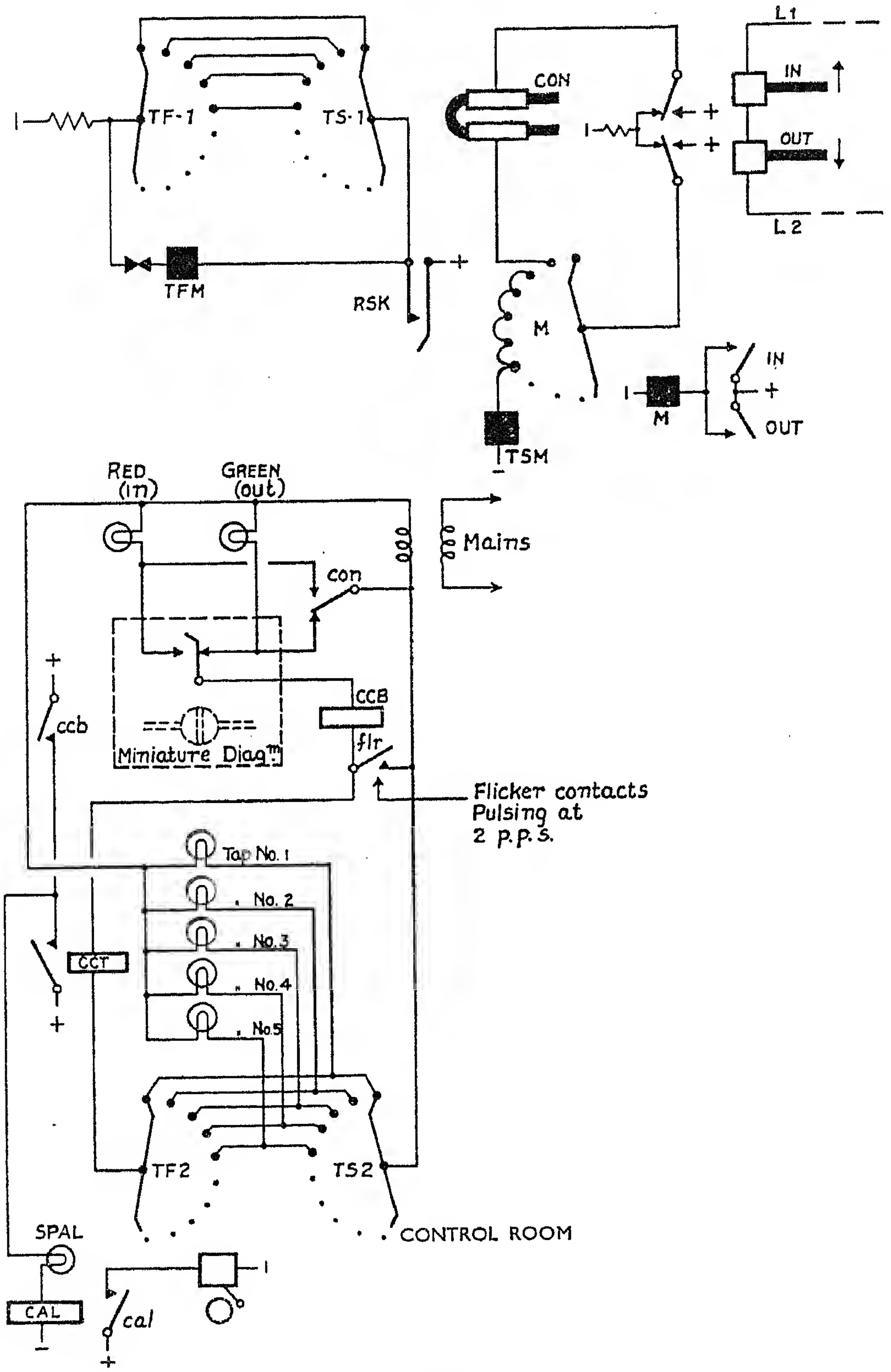


Fig. 23

magnet BRM to operate and switch BRM is driven step-by-step until its wipers stand clear of the marked bank contact. When this occurs, relay CH releases and de-energizes relay RS, thus breaking down the transient start circuit for the breaker-sending switch BSS, as will later be apparent.

When RS operates, it closes at its contacts rs1 a circuit for the upper winding of relay SE, which operates first step off-normal of switch BSS, this impulsing circuit is maintained via wiper and bank 1a of BSS. SE, at its contacts se2, disconnects the testing relay RVS from bank B2 of switch B and connects it to wiper 2a of switch BSS.

BSS now steps through its whole cycle, testing the position of all the auxiliary contacts of the circuit breakers and also those of any other groups connected

to it but not shown in the diagram. When BSS has completed its cycle, the locking circuit for relay SE via bank 1a of switch BSS is broken down and SE releases, short-circuiting E and removing the positive supply from it.

If for any reason the impulse train from the sub-station is mutilated, switch M at the control room will be off-normal when the last impulse is received. At the end of the train, relay RCO, which remained in the operative position during the pulsing period, releases, and a circuit is closed for repeat relay RP via bank M2 and wiper off-normal. RP sends at its contacts rp1 and rp2 a pulse to the substation of such direction as to operate relay RS and, by means not shown, to initiate a repeat cycle of switch BSS. A repeat cycle can be

On its second step M connects up the stepping magnet TSM of the tap signal-switch TS. This switch steps in response to the normal pulses received on polarized relay OUT.

The pulse corresponding to the tap in use, and subsequent pulses, are of reversed polarity and do not step switch TS, which thus remains in position and lights the lamp associated with the tap in use.

Indication Alarm Signals.

In series with the semaphore switch contacts representing the circuit breaker in the miniature diagram is an alarm relay CCB, which operates when the switch position does not correspond to the lamp control relay CON, as is the case when a breaker change is signalled.

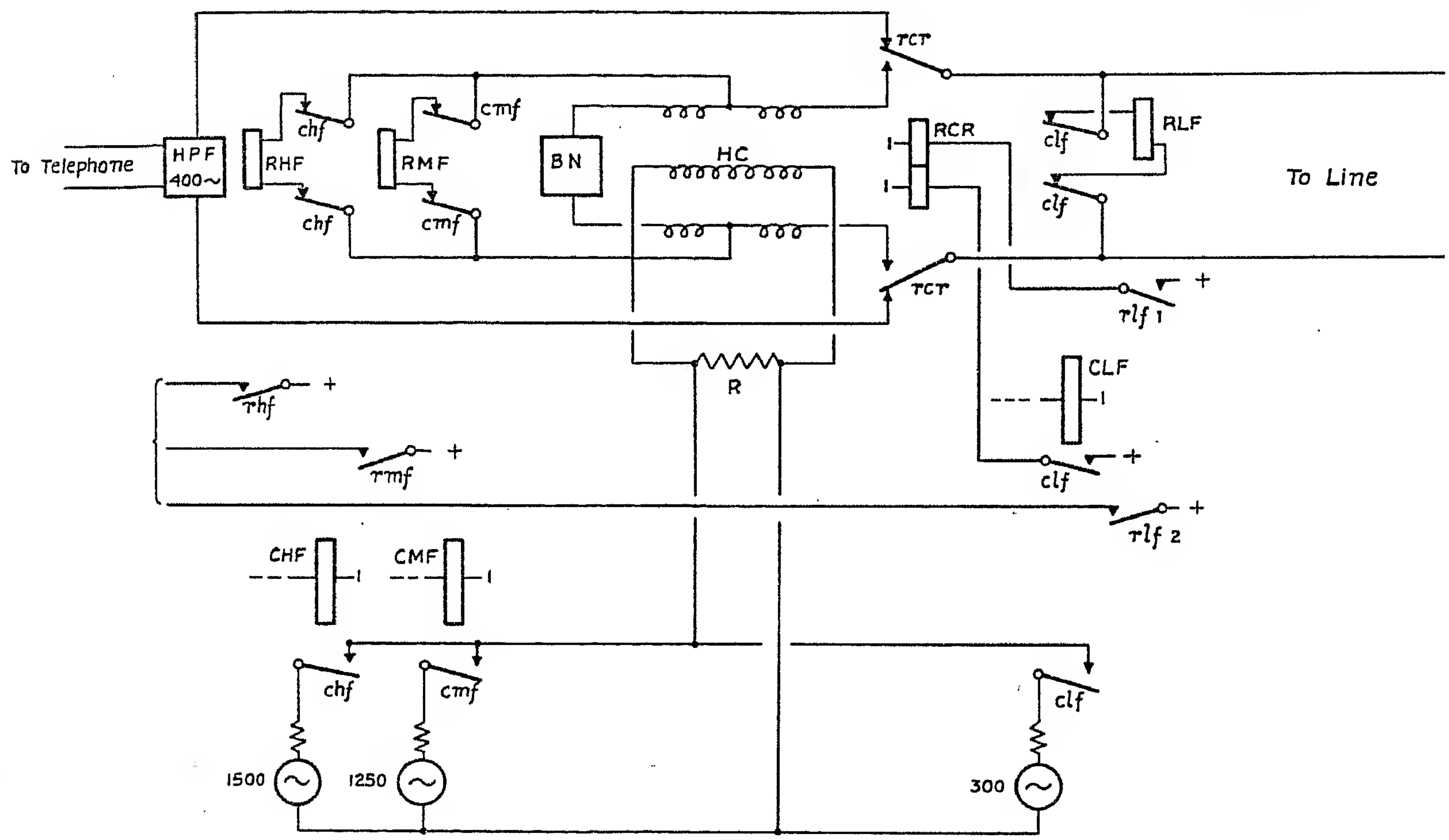


Fig. 24

initiated at any time by the control engineer pressing the check key CK, which operates relay RP in an obvious circuit.

The "in" and "out" positions of the circuit breakers are indicated by "in" and "out" lamps, which are controlled by the polarized relays CON. The setting of these relays is determined by the nature of the pulse received, positive or negative, as controlled by the testing relay RVS at the substation.

Fig. 23 shows in more detail the indicating arrangements at the control room for, in this instance, 1 circuit breaker and 5 tap-change positions.

Switch M is driven through a complete cycle by the "in" and 'out" pulses received from the substation. On its first step it connects the polarized relay CON to the local circuit of the "in" and "out" polarized line relays, and CON actuates the red or green lamp in accordance with the position of the remote circuit breaker.

When CCB operates it lights the station pilot alarm lamp in series with a common alarm relay CAL, which rings the control alarm bell.

In series with CCB is a pair of "flicker" contacts FLR, which cause the breaker-indicating lamp associated with the position from which the breaker has just changed to flicker.

The control engineer, by correcting the position of the semaphore switch on the miniature diagram, releases relay CCB, which extinguishes the station pilot lamp and cuts off the alarm bell and circuit-breaker flicker.

For each transformer there is a "tap flicker" selector TF, which is normally in a position corresponding to the last tap indication received. When a fresh tap signal is received, causing tap selector TS to move to a new contact, a circuit is completed for relay CCT in series with the flicker contacts FLR. This causes the old indication to flicker and the new indication to glow steadily. Relay CCT lights the appropriate alarm pilot

lamp and causes the alarm bell to ring until the reset key RSK is actuated. The closure of RSK completes a circuit for TFM, and switch TF rotates until it corresponds to the new indication, in which position relay CCT is released and the visual and audible alarms are disconnected.

(9) ALTERNATING-CURRENT SIGNALLING

The reasons for the adoption of alternating current for signalling purposes has already been dealt with in the introductory portion of this paper. Fig. 24 is a schematic diagram of the arrangements at one of the terminals.

The line is normally connected to the telephone circuit via the contacts of control relay RCR and a high-pass filter HPF which cuts off below 400 cycles.

Since two directions of current are used in d.c. signalling to differentiate between two groups of signals, two frequencies must be adopted when alternating replaces direct current. This would ordinarily mean that two sets of valves would have to be continuously heated and, to avoid this, a pilot frequency, lower than either of the signalling frequencies and lower than the cut-off frequency of the high-pass filter, to avoid interference with the telephone, is employed to light the filaments of the two sets of valves. This necessitates, of course, that the valve in the pilot-frequency receiver must be continuously heated.

The arrangement operates as follows:—

The pilot frequency arriving from the distant station operates the low-frequency receiver (represented as an ordinary receiving relay) RLF. RLF, in operating, energizes relay RCR, which cuts off the connection to the telephone and extends the lines through to the high- and medium-frequency receivers RHF and RMF. RLF at its contacts rlf2 has previously lit the valves of receivers RHF and RMF and these are now in a position to respond to incoming signals.

To transmit outwards, relay CLF is first operated. This operates RCR so that the lines are connected to the output windings of the hybrid coil HC, and signal trains of either of the two signalling frequencies are applied to the terminals of a resistance R connected to the input coil of the hybrid. The balancing network ensures that outgoing currents have no effect on receivers RHF and RMF.

CONCLUSION

It may be of interest to observe that there are already in service on various sections of the grid in Great Britain approximately 150 installations of the type of apparatus described in the paper, embodying automatic telephone apparatus. These have been installed by various telephone manufacturers and are of course widely scattered over very large areas. The same type of apparatus is also installed in many countries abroad.

Whilst it will be clear that the telephone apparatus described is practically inexhaustible in its flexibility of application to signalling and remote-control problems, this particular form of apparatus has also the advantage of economy as regards the signalling channel and reliability in service.

As mentioned in the first paragraph of the paper, continuity of supply has always been the principal aim of supply authorities and, since this aim now assumes the highest importance and is the first responsibility of the grid authorities, it is realized that the highest possible standard of reliability is demanded of the signalling and remote-control apparatus. The authors claim that this particular type of apparatus fulfils this stringent requirement of highest reliability. The apparatus components employed are the same as those incorporated in approximately 11 million lines of automatic telephones in practically every country of the world. This tangible evidence of the robustness of construction and stability of the apparatus components, coupled with the self-checking features of the various circuits described in the paper, together with the results already being obtained in service, appears to the authors to justify their claim.

It will be clear that within the last few years automatic telephone components have been adapted with success to the solution of problems arising in connection with the control, distribution, and protection, of power networks. Telephone apparatus is thus now working in the closest conjunction with the power equipment itself and is providing the rapid and accurate control of power so essential to the efficient running of a large power network.

The authors believe that many new problems in regard to the remote supervision and control of power networks will emerge from time to time and will be solved by the increasing incorporation of the type of apparatus described in the paper.

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[The discussion on this paper will be found on page 120.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 7TH FEBRUARY, 1936

Dr. William Wilson: This paper is the happy result of co-operation between two radically different types of electrical engineers who have been working on different lines, namely the power engineer, who works and thinks in kilo-amps., and the communication engineer, who works and thinks in microamps.

The great object of the work described in the paper is to save channels, but the authors do not give a very complete list of the types that are available. Those described have certain drawbacks; in the first place, the overhead wire mounted on the same poles as the feeder may be simple enough with comparatively low-voltage wood-pole lines (up to 33 kV) which are spaced fairly close together, but it is a very difficult matter to apply remote-control channels to grid towers. The difficulties of wayleaves are so great that towers tend to be spaced farther and farther apart, and this renders the application of auxiliary conductors to them more and more difficult. Secondly, the separate pole-line not only introduces another source of expense but it means that these auxiliary conductors, which should be more reliable than the main feeder, are actually less reliable. Thirdly, the line can be laid underground, and I agree with the authors that this type of channel is the best when it can be secured. Under city conditions or in congested districts, however, the expense which it involves is enormous. I have one case in mind in the Birmingham area where a 132-kV grid line was provided with underground pilots, and the difficulty of trenching and general construction was so great that the cost was comparable with that of the feeder itself. Finally, the method of hiring G.P.O. cores sounds simple, but it has definite drawbacks. These cores were intended for a totally different purpose, and they are not exactly suitable for their present use. For one thing, a number of restrictions have to be observed; e.g. these channels can only be used for direct current, for voltages not exceeding 50 volts, and for currents of not more than 15 milliamps. Their capitalized cost is very great; they are really one of the most expensive types of pilot. In addition, such a channel is not under the control of the engineer responsible for the line, which involves two serious drawbacks, namely (*a*) the right to use the line may not be granted absolutely to the power authorities, in that the G.P.O. may reserve the option of withdrawing any particular channel in an emergency; (*b*) the lines are subject to testing by engineers not connected with the power supply, who may conceivably apply a magneto to the wrong line and thus black-out a whole district. These defects are not possessed by two other kinds of channel which are not mentioned by the authors.

One is the use of carrier currents, whereby the main lines are employed for carrying the impulses. The only cost involved is in the terminal equipment, and if the line exceeds, say, 10 miles in length the method becomes an economical proposition. It is greatly to be regretted that the Central Electricity Board have not anywhere adopted this system. It has, however, been employed on certain company-owned schemes, e.g. that of the Grampian Electricity Supply Co. In this case it is relied upon for the entire supervisory control between the power station at Tummel and the substation at Abernethy; the carrier currents being transmitted over 132-kV lines. The programme includes the extension of the carrier system to embrace the entire control of the hydro-electric power station at Rannoch, by means of the existing 33-kV lines.

Secondly, there is the earth-core pilot system, which makes use of four cores contained in the centre of an otherwise standard earth wire. This involves no particular addition to the overhead line. The extra cost and weight of the four cores, which are enclosed in a small lead sheath and insulated with oil-paper, is very little. It will be seen that the pilots are supported in an especially robust manner, as well as being efficiently safeguarded both mechanically and electrically.

This latter type of channel will also serve for any form of protection, and it should be realized that there are two different types of protective gear. The first is represented by the lock-in type mentioned by the authors, which is one of a family of schemes in which a d.c. impulse conveys a signal from one end of the pilot to the other to the effect that the current in the main conductor has reached overload proportions, or has reversed. This type of protection can be used with any species of pilot, including telephone cores and carrier channels. It is, however, relatively elaborate and expensive, and since the main current has to exceed the normal value before protection is given, it is not quite so sensitive as might be desired.

The other form of protection is represented by the Merz–Price or McColl gear and may be called the quantitative type, since it depends on the current entering a conductor being compared with that emerging. As soon as the latter exceeds the former by a definite amount in the case of the Merz–Price gear, or a definite proportion in the case of the McColl, tripping occurs. This is obviously a sounder method than the previous one, since it is more sensitive, more discriminative, and a great deal simpler; but, on account of its requiring that an alternating current of varying magnitude shall pass through the pilots, it is not applicable to all types of auxiliary conductor. Pilot-earth wires are used for this purpose in at least two parts of the country, notably in connection with the Notts and Derby 33-kV ring main. In another area, the four cores are used not only for protecting two separate e.h.t. lines on the quantitative system but also for telephony by means of a phantom circuit superposed upon the existing four conductors.

Mr. E. M. S. McWhirter: I should like to refer to two points which might be considered to amplify those of the authors. The first is that with the coming of automatic voltage regulation of a.c. systems the need for manning substations has almost entirely disappeared. Secondly, as regards the centralized control room, there is a very strong psychological point which is not emphasized in the paper, namely that the modern control engineer should be completely removed from all the apparatus. Such things as breakdowns can be very disturbing to a control engineer.

Regarding the question of pilot wires, the authors prefer these to be laid underground, and I endorse their

preference, but where they are laid in the same trench as a cable—and cables owned by power companies frequently are so laid—there is still a necessity for protecting them in the ways which the authors describe for the aerial cable, or in other ways which have been adopted and have proved successful. These points should not be overlooked, because the protective system represents a fair proportion of the total price of the equipment.

I would mention one system which is used by the C.E.B. in the Mid-East England and North-East England Areas, in which an isolating transformer only—insulated to the same degree as those described in the paper—forms the barrier between the P.O. rented lines and the high-voltage supplies connected to the switchgear, etc., in the station. This method, whilst it is virtually an a.c. method, differs from the voice-frequency method in that it has no attendant valves or voice-frequency generators. It consists simply of reversing on an ordinary relay a 50-volt battery on the station side of the transformer, suitably designed to transmit the impulses through to the line at the speeds of impulsing mentioned in the paper. These impulses are received on sensitive relays of the telegraph type, which prove most robust, and are then converted back to the ordinary telephone type of counting mechanisms. By this means one isolating barrier only is required, instead of the isolating-barrier relays, isolating transformer, and motor-generator, employed in the method described by the authors.

I should be glad to know the authors' opinion of the use of gaseous discharge tubes for protection purposes. In the early designs of such tubes considerable ageing occurred for periods of 1–3 years, with the result that the tubes originally designed to break over at 450 volts or so were found to be going over at more like double that voltage.

The authors mention that ordinary telephone dry paper-insulated cables are suitable for pilot cables. I agree; with the proviso that one should insulate the conductors one from the other to a higher degree than normally obtains in telephone cables, particularly if they are to be subjected to high-voltage shocks when faults occur. The reason for this is the fact that, if the spark-gap on one pilot wire flashes over before the other, then momentarily the full voltage stress will exist between the two wires; and as repairs are always a costly business it is better to provide this safeguard in the actual design of the cable.

I should be glad to know whether the authors employ relays with twin contacts, such as are now standardized for telephone equipment in this country. This point is not made clear in the paper.

From the great variety of the control diagrams shown in the paper it is obvious that the various power engineers who have been consulted by the authors as to their requirements have each put forward their own particular views. A certain amount of disparity may also be put down to the development of the art in the passage of time. One would, however, very much welcome a discussion between power engineers, and particularly those who are definitely associated with the control side, as to the pros and cons of the various diagrams. It would be very useful as a guide to further development. One type of control diagram which has been adopted very largely is the semaphore type with lights, instead of a disc which rotates under the action of a small electromagnet behind. Two lines of light are produced, one vertically and the other horizontally. With this type of indicator, and using a flashing supply and a flicker supply (supplies of energy interrupted at two different speeds which are very easily and readily distinguished one from the other), it is possible to get quite a combination of signals and to indicate on that one indicator without any moving parts either that the switch has been tripped; or that it has been selected ready for control; or how it has been tripped—whether on overload or by another protective system. This arrangement is an important step forward when considered for a large wall diagram—perhaps 8 ft. high—compared with small rotating discs at the top which have to be attended to frequently.

Turning to the question of metering, it is interesting to note that there are available both stepping indicators giving spot readings, and also the continuous type. Here, again, the opinions of power engineers as to the relative merits of the two systems would be very useful. I think they would choose the continuous type of metering. Just how far is a man controlling a system, where he is concerned rather with the general overall picture, really interested in watching the fluctuations of a meter? The stepping-meter indicators with which I have had something to do* are interesting, as distinct from those described. They are similar in all respects except that they move in both directions—up and down—instead of having to return to zero. Voice-frequency metering is a very interesting development, and I hope to see it very largely adopted.

This paper has been produced by men who, whilst basically telephone engineers, have interested themselves in the problem of remote control of power networks. They apparently adhere to the type of circuit diagram and description that persists in the telephone world, because it is almost the only simple presentation available. Control engineers and power engineers generally prefer circuit diagrams based on their own methods, and their diagrams are quite different in this respect, namely, that they draw two broad lines somewhere on the paper and string all circuits across in straight lines between them and similar circuits; to draw a circuit diagram of a remote control system on such principles would be rather difficult.

Mr. H. C. Ogden: We cannot expect remote control apparatus to give 100 per cent performance; we must expect an occasional failure. I think, however, that, particularly with remote control apparatus, it is essential that any failure should be failure of a switch to operate, rather than the operation of the wrong switch. The first type of fault may be inconvenient, but the consequences of the latter may, quite literally, be fatal. The authors touch on this point on page 114 so far as it concerns tripping; it is still more necessary when closing is concerned. The authors also refer to the necessity for a complicated code in inter-tripping to prevent incorrect operation. In a centralized control system all the pilot wires radiate from a single point, and there is certain

* *Journal I.E.E.*, 1935, vol. 76, p. 156.

apparatus at that point which is common to all the circuits. It is therefore advisable to have a completely distinct code for each section of the network, in order to guard against incorrect operation not merely by external interference on the pilots themselves, but by the actual straying of a code from the correct path in its own apparatus. In addition, simultaneous happenings on different parts of the network should not interfere with the correct operation of the control gear in each case.

The paper makes no reference to the need for automatic synchronizing. Probably this is not required on the majority of distribution systems, but where there is any possibility of sections of the network getting out of synchronism, remote control is of little value unless there is some automatic synchronizing apparatus to take charge of the closing operations once the control engineer has initiated them.

A further point which is not mentioned is the power supply to the telephone equipment. It is necessary that any batteries which are employed should have ample reserve to cover any possible failure of the main power supply, and that the apparatus should work satisfactorily under fairly wide variations in battery voltage.

The power engineer is apt to look with misgivings at the comparatively flimsy contacts associated with telephone-type equipment. In this connection, experience with one section of the grid to which the authors refer in the paper may be of interest. This shows that after a reasonable time has been allowed to elapse from the commissioning of the equipment, to allow the inevitable dry joints, etc., to show up, and granted reasonable maintenance, in a substation where one switch is closed and opened once a day one can expect the equipment to fail to operate once in 9 years. With that record in view I feel that the authors' claim to reliability is justified.

Mr. J. E. Collyer: The design of supervisory control and indication systems depends to a very large extent upon the type of apparatus employed, and this paper gives further proof of the suitability of automatic telephone apparatus for that class of work. In this connection I should like to endorse the authors' statement in the concluding paragraphs of the paper.

Dr. Wilson referred to the fact that the paper makes no mention of carrier systems. By "carrier" system I mean one in which the line signal is of a frequency of the order of, say, 150 kc and is superimposed upon the power line itself. The great advantage of the system is the saving of the cost of pilot wires. There are limitations to the economic adoption of the carrier system, but it is coming into greater use. The system installed at Abernethy by the Grampian Electricity Supply Co. has been in operation now for several years.

I should also like to refer to the increase in the use of voice-frequency signalling, because I think that in time d.c. signalling will only be used on comparatively simple systems where the lines are short and the line conditions good. There is a tendency nowadays to hire telephone lines from the Post Office; but as P.O. lines are designed primarily for the transmission of telephone speech it seems reasonable to use for the line signal in such cases an alternating current of speech frequency. Voice-frequency signalling has many advantages over d.c. signalling. It can be transmitted over all types of communication channels. It offers a wider choice in line signalling. It is not affected to the same extent as d.c. signalling is by the variations in the line conditions, and also it permits of a relatively simple arrangement for the high-voltage separation sometimes required between the line and the line signalling equipment.

Another point to which I should like to refer concerns the switch-position checking, a very important factor which has contributed to the success of remote control systems. Two methods of checking are mentioned—the revertive impulse method and the impulse counting method; but there is a third method, and one which has been used most successfully, called the check-back. This system has been used quite as much as, and probably more than, any other. In this arrangement the train of impulses for operating the distant switch is sent over the line and is checked by a train of impulses being returned corresponding to the position taken up by the receiving switch. If the impulse-train returned corresponds to the impulse train sent out, one knows that the switch has been correctly positioned. A big advantage of this over other systems is that a number of settings can be made and checked in one revolution of the switch.

An interesting development is the metering system described by the authors on pages 111 and 112. This is an interesting solution to a difficult problem, and it is one of the best metering systems I have seen. Using voice-frequency signalling, its indications can be communicated over all types of channels, and it is not affected so much by line conditions as are other systems. Another point is that it enables several telemeters to be run over the same pair of wires.

All these advantages can also be found in a system of remote metering recently developed, called the frequency system. In this arrangement the supply to the meters is fed on to a movement such as a watt-hour movement, on the shaft of which is a notched disc. Variations in the supply will cause variations in the speed of the shaft, and therefore of the notched disc. An optical system projects a beam of light through the notches of the disc on to the photoelectric cell, and the interrupted current from this is amplified and then converted, by means of an oscillator and modulator, into an interrupted voice-frequency current. This is received on the amplifier-rectifier at the control station, where it is converted into interrupted direct current for operating the receiving relay, which thus vibrates in accordance with the speed of the disc. The circuit of the recording meter contains the contacts of the vibrating relay, the arrangement being such that the position of the meter pointer is dependent upon the speed of vibration of the relay.

Mr. W. Phillips: I will confine my remarks to the remote indication of meter readings, and will mention one or two simple methods in use for this purpose on the grid.

Some 4 or 5 years ago the manufacturing firm with which I am associated supplied a number of "direct connected" meters for use with automatic-telephone type supervisory gear. The readings to be reverted

were those of ammeters and voltmeters, and the instruments consisted of permanent-magnet moving-coil indicators, worked through dry-type rectifiers. Each of the ammeters was connected through pilot wires to a special "separating current transformer," which reduced the secondary current of the measuring transformer to a few milliamperes. The secondary winding of the separating current transformer was connected in turn to the dry-type rectifier. The separating current transformer was placed at the transmitting end of the pilot wires, and the indicator at the receiving end. The voltmeters were also worked through dry-type rectifiers, the necessary swamp resistance being inserted in the a.c. side of the rectifier. The current transmitted along the pilot wires was unidirectional.

Mr. Fawssett has recently employed a similar arrangement on the North-Eastern Electric Supply Co.'s system, but in this case alternating current is transmitted along the pilot wires and the rectification is carried out at the receiving end. Another method due to Mr. Fawssett makes use of a thermocouple. The current to be measured is fed into the heater of the thermocouple, and the resultant direct current is fed along the wires and is received at the far end. This method is used a great deal in Canada.

I should like to make a few remarks on a system for reverting instrument readings that the authors have not mentioned, and of which a number are in use. This method, the Elliott-Shotter transmission system, may be called a direct operating method; it employs the motion of the measuring instrument to produce the deflection of the receiving instrument without the aid of contacts, relays, or motors. The receiving instrument follows the movement of the transmitting instrument simultaneously, and without any interval or loss of time, and is moreover self-synchronizing. The transmitting instrument may be of any type in which the torque for full-scale deflection is of the order of 1 g-cm. Obviously it can also be employed to transmit any change in angular or linear position, such as water level, damper position, bridge opening, and so on. The receiving instrument is of the permanent-magnet moving-coil type and can be of any convenient size or shape.

The transmitting mechanism consists of an aluminium or copper loop, embraced by two small alternating-current electromagnets. One of the electromagnets has a complete magnetic core, whereas the other has a narrow gap through which a sloped portion of the loop moves. The combination of the two iron circuits, on each of which is wound a coil of wire, forms, with the loop, a transformer of variable ratio. The loop is rigidly fixed to the moving part of the transmitting instrument, and as the transmitting instrument alters its deflection the loop moves through the air-gap of one of the electromagnets and thus alters the electrical coupling between the windings of the two electromagnets. In this manner the e.m.f. induced in the winding connected to the line, varies with the position of the transmitter, and a corresponding change in the deflection of the receiver is produced. One of the electromagnets, which may be called the input magnet, is connected to any convenient source of alternating current, and the second or output magnet is usually connected to a dry type of rectifier; thus direct current is employed for transmission. This system is employed also for transmitting the indications of wattmeters, and can be arranged to give sectional and total summation of a number of circuits. A modification of the system enables the power consumption in kilowatt-hours of any number of circuits to be registered, and also the maximum demand to be indicated or recorded at any distance. In this arrangement the transmitting mechanism is attached to a standard integrating meter, and as the coupling between the input and output circuits of the transmitter is purely electrical no mechanical restraint or additional friction is imposed on the meter. The transmission is effected by impulses of direct current without the interposition of relays or contacts.

Mr. F. C. Knowles: In the very early days of the grid remote metering some of us who had struggled with remote indication long before that time were met with the problem of conveying meter readings over Post Office circuits. I remember what a shock it was to me when I asked what was the resistance of those lines, and was told "infinity." I was also told that the connection would not always be made through the same repeater station or the same lines. When investigating the telephone side of the problem I came across a number of diagrams compared with which those included in the paper are quite simple, and I was rather fascinated with the method of diagrammatic representation adopted by telephone engineers. I would commend to my fellow instrument engineers the study of diagrams of this nature.

There is a very large field for remote control, apart from the power networks. For example, the consumer of power in a colliery or large works also requires to know what is going on in the various parts of his plant, and that of course in many cases is a much more simple problem because it is possible to run private lines and also to use some of those other systems of remote indication which cannot be used for metering on the systems described by the authors.

No mention is made in the paper of the system which is used in the control room of the Bankside power station for remote indication, namely the time-period system developed by Leeson, Harle, and Lambert, which I briefly described a few years ago before this Section.*

Fig. 18 shows two shafts which are mounted one above the other. I think that in practice those two shafts are generally at a considerable distance from one another and there is an electrical link between them.

It would be useful if the authors would give the patent numbers of the systems they describe, or the references to them in published papers. I would point out that there is no mention in the Bibliography of a paper read before this Section a year or two ago by Messrs. Midworth and Tagg.† I think that this should be included.‡

So far as the apparatus which the authors have placed on view this evening is concerned, I have no doubt that in a few years' time equipment of this type will be replaced by apparatus in which the indications will be given and control effected without the moving systems which they are now employing.

Mr. J. D. Peattie: Several previous speakers have

* *Journal I.E.E.*, 1931, vol. 70, p. 39.
† *Ibid.*, 1933, vol. 73, p. 33.
‡ Since added for the *Journal.*

referred to the valuable assistance given by communication engineers in the solution of power engineering problems, particularly by the use of apparatus developed for automatic telephony. The same arguments apply to the provision of the communication channels themselves. In settling their policy for the provision of the communication circuits required for the control of the grid the Central Electricity Board decided to avail themselves of the national services offered by the Post Office in the provision of such circuits, and therefore hired from the Post Office a complete system covering Great Britain with the exception of North Scotland. This system comprises over 6 000 circuit-miles of channels, of which over 80 per cent are underground. The Board have no reason to regret their decision, which has resulted in a rational use of the existing national communication system. The independent provision by the Board of a similar service would have involved unnecessary capital and running expenditure.

Dr. Wilson suggested the wider application of the carrier-current system to power lines. Such systems seem to be best suited for use on simple radial power systems, or on long transmission lines with no intermediate tapping points. The grid is essentially a network built up of closed rings with intermediate switching stations. In general, the control centres are not suitably placed for easy connection to points on the power network, and the provision of suitable carrier-current channels between the control rooms and grid points is therefore at present not possible.

Mr. E. S. Ritter: Referring to the method described in the paper of sending voice-frequency signals over a line with time-intervals in between, I should like to point out that when these signals are transmitted over an electrically long transmission line, the signal currents, if they are of voice frequency, do not rise instantaneously to their maximum amplitude. The envelope of the signals gradually builds up to a maximum and then, on the cessation of the signal, gradually falls away to a minimum. The time-interval at the receiving end is therefore not necessarily the same as the time-interval at the transmitting end. I should like to ask whether any errors in the reading are apparent, arising from this cause.

In Fig. 24 the authors show in a square a piece of apparatus labelled "B N," which I imagine is a kind of balanced network. I presume that its function is to divide up the currents so that the network impedance balances the line impedance, and I should like to know whether it really does so.

Other speakers have drawn attention to the use of what they call "telephone-type diagrams," or what I prefer to call "detached-contact diagrams," where the relay contacts are dissociated from the coil of the relay. While I agree that this practice simplifies the reading of the diagram, I feel it is a mistake even for telephone engineers to put the contacts of a relay on one diagram and its coils on some other diagram. I admit that it is necessary in certain cases, but I think that it should be avoided wherever possible. In Fig. 15, for example, on the right-hand side of the chain-dotted lines one sees contacts labelled "imp 1," "imp 2," "rv 1," and "rv 2," which do not seem to have any associated coil. A weakness of telephone engineers is that they employ descriptions for the relays, such as "RSR," without disclosing the derivations of the abbreviation. Presumably in Fig. 15 "imp" stands for "impulse," but surely it would be very simple, the first time that these letters appeared in the circuit description, to show in full their derivation. A method of locating the contacts of a relay when describing a complicated circuit diagram is to follow the relay contact code with a "map reference," the diagram being divided into squares like a map. This method is, however, only necessary in large and complicated circuit diagrams. I should like to draw the attention of power engineers to the fact that the British Standards Institution have issued a Specification which gives standard conventions for use in diagrams for power work and for radio and telephone work.*

Mr. H. H. Harrison: Mr. Ritter's point about the building-up time of voice-frequency systems on electrically long circuits hardly applies, I think, to such schemes as the grid schemes, because there the telephone lines are, I imagine, electrically short.

Messrs. G. A. Burns and **T. R. Rayner** (*in reply*): Several speakers have pointed out that the carrier-current channel is not discussed in the paper. Undoubtedly, this type of channel will be increasingly used, but probably not to any very large extent on such systems as the British grid.

As pointed out by Mr. Peattie, the full advantage of a carrier-current system can be obtained only when the control room is situated at an electrical centre of the network. With a large and complex system of power lines there is not one centre but several, and it becomes necessary to provide apparatus at these centres to receive the carrier signals and retransmit them in a different form to a second somewhat similar set at the main control room for the area.

Dr. Wilson points out that the Post Office lines are not suitable for all forms of protective circuits; this is agreed, but during the past few years considerable advances have been made in the direction of obtaining correct discrimination with the assistance of Post Office lines, and there are indications that further advances will be made in the near future.

The testing of lines by the Post Office maintenance engineers has in the past caused some little inconvenience, but with a properly designed system no black-outs will occur due to magneto ringing or to any other form of line testing. It is the practice of the Post Office to mark supervisory pilot leads specially, in order to prevent unnecessary and unauthorized interference, and it is now found that very little trouble is experienced from this cause.

The telephone line hired from the administration has one great advantage over power-line carrier or earth-wire cable, or even, to a lesser extent, pilot cables owned by the power company, namely that there is no reason to suppose that the telephone line will be disturbed by any fault occurring on the power network. Amplifying this point somewhat, let us assume that we have a protective circuit operating on a carrier channel over the power line. When a fault occurs on the power line, there will inevi-

* B.S.S., No. 530—1934.

tably be considerable voltages impressed upon the carrier equipment, thus causing the latter to operate while it is not in a steady state. We agree that the carrier equipment can be made to function satisfactorily with almost any type of fault on the power line. At the instant the fault occurs, however, the severe transients which result are likely to give rise to corresponding transients in the carrier channel.

Dr. Wilson suggests that we have not mentioned the earth-core pilot; this was not specifically mentioned as it is a particular form of cable carried on the main transmission poles, the advantages of which are discussed.

Mr. McWhirter describes a system of signalling in which the isolating relays referred to in the paper are dispensed with and impulsing is carried out through an isolation transformer. For a simple system this method may have advantages; but when the circuit has to be extended to provide telephone or other facilities over extension lines, trouble is likely to be experienced owing to a fault on the extension line throwing the whole equipment out of commission. Furthermore, the necessity of maintaining a high impedance on the local side of the isolating transformer almost inevitably gives rise to considerable speech-transmission losses.

There is no doubt that some hardening of gaseous discharge tubes does take place over a period of years. Our experience, however, is that they will operate satisfactorily for a long time except on circuits with a very bad fault record. Here the frequency of the faults not only makes it advisable to change the tubes at fairly frequent intervals but also leads to redesign of the power circuit itself, after which no further trouble is experienced with the gaseous discharge tubes.

The firm with whom we are associated make it a practice to use not twin contacts such as are employed in telephone apparatus, but two separate springs, each having its own contacts and with the springs wired in parallel. In our opinion this is even better than the twin contacts, as it allows the adjustment of the relay to be very poor indeed before faulty operation occurs.

Mr. McWhirter also asks that there should be a discussion between power engineers before deciding what is the best type of diagram. With this suggestion we are in agreement. There is no doubt that a very large proportion of the cost of supervisory equipment could be saved if only a more or less standard type of diagram could be used for all cases. With regard to the types of drawings employed, it has been our experience that when a power engineer fully grasps the method of drawing a detached contact drawing, he has no desire that the supervisory drawings should be in the typical form adopted by power engineers, but rather that the symbolism adopted in detached contact drawing for his own protective gear be used. This results in very great simplification of these drawings.

Mr. Ogden's figures, which support our claim concerning the reliability of the equipment, are interesting, and in a few years' time it is to be hoped that we shall be able to get some figures of this nature classified in such a manner that any weak points in the system may be corrected.

The paper does not make any reference to synchronizing, but this offers no difficulty, it being quite simple to impress the two voltages whose phase relationship is to be determined on separate carriers, transmit them to the central indicating station, and employ a third carrier for switch-closing or speed regulation.

Mr. Ogden, although stating that the telephone type of relay contact gives good service in practice, still refers to the contacts as flimsy. We suggest that in power protective circuits there are very few relays which give such a high contact pressure as that given by the average telephone relay.

Mr. Collyer mentions a third type of switch-position checking. It appears to us that this is, in principle, the same as the revertive impulse method. Under certain circumstances time is saved by checking the pulses in batches rather than individually, as described in the paper.

A further form of meter reading described by Mr. Collyer is interesting, but from his description it is not clear how the difficulty of transmitting positively the fact that a certain station is "floating" is overcome. There are many satisfactory ways of obtaining a meter reading from some meters and similar equipment while a reasonable amount of power is being exported or imported; but considerable difficulties arise when no power is flowing, and it cannot be considered satisfactory to assume that when no impulses are being received the station is floating. An auxiliary circuit must be maintained to check that the equipment at the far end is operating satisfactorily. With the system described in the paper this check can be obtained automatically if the scale of the receiving instrument is made slightly less than the full angular movement of the receiving meter.

Mr. Phillips describes one of the large number of metering systems which are very suitable for simple indicating systems; and many of them are, in fact, used as part of a complete long-distance supervisory-control equipment. Without the addition of some switching apparatus they are, however, uneconomical in the use of pilots.

Mr. Ritter points out that there will be inevitable distortion in the impulse transmitted by any voice-frequency metering system. This, however, is not serious, since delay in the rise and fall of the current will be approximately the same whatever the length of the impulse and thus can easily be compensated for by a slight zero adjustment on the receiving-end meter. With very long lines giving serious echo phenomena more elaborate steps have to be taken in order to obtain a reasonably accurate indication.

INSTITUTION NOTES

NOMINATIONS FOR ELECTION TO THE COUNCIL

In addition to those members nominated by the Council (see vol. 78, page 725) the following have been nominated for ballot as Ordinary Members of Council:—

Members.

R. W. L. PHILLIPS. (Nominated by W. Burton, M.Eng., Dr. F. W. Carter, M.A., F.R.S., A. C. Cramb, A. Lisle, M.B.E., H. Marryat, H. Nimmo, H. Trencham, Lt.-Col. W. A. Vignoles, D.S.O., T. Wadsworth, M.Sc., and H. W. H. Warren.)

P. J. ROBINSON. (Nominated by L. Breach, G. P. Dennis, P. M. Hogg, H. C. Lamb, A. C. Livesey, G. H. Nisbett, J. S. Peck, F. E. Spencer, Prof. F. J. Teago, D.Sc., and B. Welbourn, M.Eng.)

Associate Member.

W. J. OSWALD. (Nominated by A. S. Blackman, A. P. MacAlister, A. E. McKenzie, F. D. Napier, J. H. Parker, F. Pooley, D. A. S. Porteous, G. M. S. Sichel, J. E. Tapper, and J. W. J. Townley.)

INFORMAL MEETINGS

186TH INFORMAL MEETING (6TH JANUARY, 1936)

Chairman: Mr. G. F. Bedford, B.Sc.

Subject of Discussion: "Sound Recording and Reproduction" [introduced by Mr. S. S. A. Watkins, B.Sc. (Eng.)].

Speakers: Dr. L. E. C. Hughes, Messrs. F. Jervis Smith, P. Voigt, B.Sc.(Eng.), R. P. G. Denman, B.A., N. D. Angier, W. F. Floyd, P. Wilson, W. Morgan, E. S. Ritter, E. S. L. Beale, W. St. G. Penstone, E. F. Clark, H. Bourne, M.C., and J. H. Riley.

187TH INFORMAL MEETING (20TH JANUARY, 1936)

Chairman: Mr. M. Whitgift.

Subject of Discussion: "Small Motors" (introduced by Mr. R. A. Lochner).

Speakers: Messrs. A. N. D. Kerr, R. H. Young, B.Sc. (Eng.), G. F. Bedford, B.Sc., J. O. Turnbull, Forbes Jackson, S. A. Stevens, J. E. Macfarlane, B.Sc.(Eng.), A. W. Fisher, R. V. Powditch, G. Davidson, P. Jackson, L. H. Bainbridge-Bell, J. M. Reekie, E. F. Clark, and D. St. A. Butcher.

188TH INFORMAL MEETING (3RD FEBRUARY, 1936)

Chairman: Mr. F. Jervis Smith.

Subject of Discussion: "The Superimposition of Carrier Waves on Distribution Systems" (introduced by Mr. H. P. Barker).

Speakers: Messrs. G. H. Fowler, E. S. Ritter, W. St. G. Penstone, Lieut.-Commander E. L. B. Damant, Messrs. A. G. Kemsley, M. G. Scroggie, B.Sc., D. St. A. Butcher, H. Brierley, J. I. Bernard, B.Sc.Tech., J. F. Perrin, E. E. Sharp, and F. Jervis Smith.

189TH INFORMAL MEETING (24TH FEBRUARY, 1936)

Chairman: Mr. L. M. Jockel.

Subject: "Multiple Earthing or Leakage Trips" (introduced by Mr. T. C. Gilbert).

Speakers: Messrs. A. F. W. Richards, A. J. Bousfield, F. E. Rowland, N. Elliott, B.Sc., H. G. Taylor, H. W. Grimmitt, H. J. Cash, P. J. Higgs, A. Morgan, S. C. Bartholomew, M.B.E., G. H. Fowler, T. G. Partridge, S. A. Stevens, E. F. Clark, S. White, and J. M. Kennedy, O.B.E.

190TH INFORMAL MEETING (9TH MARCH, 1936)

Chairman: Mr. J. F. Shipley.

Subject of Discussion: "Electric Furnaces" (introduced by Mr. W. S. Gifford).

Speakers: Messrs. J. I. Bernard, B.Sc.Tech., J. F. Perrin, A. Morgan, P. J. Higgs, D. Williamson, D. F. Campbell, L. W. Wild, J. W. Ackerday, L. M. Jockel, J. F. Shipley, P. P. Wheelwright, J. H. Marsh, B.Sc. (Eng.), H. D. Barlow, J. E. Gamage, J. J. Fisher, and W. F. Comben.

191ST INFORMAL MEETING (23RD MARCH, 1936)

Chairman: Mr. A. F. W. Richards.

Subject of Discussion: "Electricity Supply to, and the Equipment of, Trolley-buses" (introduced by Mr. J. H. Parker).

Speakers: Messrs. W. E. Warrilow, J. D. Collier, F. Jervis Smith, H. Brierley, S. J. Patmore, R. L. Acland, B. C. Ward, A. N. D. Kerr, W. M. Mordey, A. Morgan, R. Grigg, J. D. Dennison, E. S. Ritter, L. M. Jockel, J. H. C. Brooking, G. F. Bedford, B.Sc., A. H. Bennett, C. C. Hall, and P. Gunn.

192ND INFORMAL MEETING (6TH APRIL, 1936)

Chairman: Mr. M. Whitgift.

Subject of Discussion: "That the Electric Supply Industry should sell Service" (introduced by Mr. N. F. T. Saunders, B.Sc.).

Speakers: Messrs. C. R. Westlake, G. F. Bedford, B.Sc., Forbes Jackson, C. Hazel, A. G. Kemsley, Miss C. H. Haslett, O.B.E., Miss M. Reading, Messrs. A. F. W. Richards, W. E. Warrilow, E. E. Sharp, D. B. Williamson, B.Sc., L. C. Penwill, Mrs. B. G. Copland, Messrs. F. B. P. Pearce, G. Davidson, P. P. Wheelwright, and D. St. A. Butcher.

OVERSEAS ACTIVITIES

Argentina

At the Seventeenth Annual General Meeting of the Local Centre, which was held at Buenos Aires on the 6th December, 1935, under the chairmanship of Mr. R. G. Parrott, the Report of the Local Hon. Secretary (Mr. R. G. Parrott) for the year ended 30th November, 1935, was presented and adopted. The Report contains

a list of the Centre's activities during the year, which included, in addition to the meetings already recorded in the *Journal* (*see* vol. 77, p. 573), the following:—

1935	
25th July.	Paper by Mr. L. P. Thomson on "Electric Traction on Subways."
10th Aug.	Visit to the "Italo" Power Station, New Port.
21st Aug.	Paper by Mr. E. Berry on "Cosmic Rays."
7th Sept.	Visit to substations and new sections of the Chadopyf Subway.
26th Sept.	Paper by Mr. G. W. Munday on "Some Notes on 'Metadyne.'"

The meeting was followed by the Annual Dinner of the Centre, which was attended by 34 members and guests.

Australia

New South Wales.

The Annual Smoking Concert arranged by the Local Committee was held at the Carlton Hotel, Sydney, on the 30th August, 1935. The attendance totalled 80, and included representatives of the Institution of Civil Engineers, the Institution of Mechanical Engineers, the Institution of Engineers (Australia), the Institution of Radio Engineers, and the Royal Australian Corps of Military Engineers.

Queensland.

At a meeting arranged by the Local Committee and held at Brisbane on the 26th July, 1935, Mr. W. I. Monkhouse in the chair, the paper by Mr. W. Fennell entitled "The Effect of Legislation and Regulations upon Electricity Distribution" (*see* vol. 77, p. 663) was reviewed by Mr. A. E. Axon, Associate Member, who compared the legislation referred to in the paper with that existing in Queensland. Messrs. J. E. Morwood, G. G. L'Estrange, E. J. Sharman, J. M. Bruce, and F. R. L'Estrange, took part in the discussion which followed. A vote of thanks to Mr. Fennell for the paper, and to Mr. Axon for his review of it, was carried with acclamation.

At a meeting held at Brisbane on the 13th September, 1935, the paper by Mr. T. P. Preist entitled "Electrical Control of Road Traffic by Vehicle Actuation" (*see* vol. 77, p. 149) was reviewed by Mr. E. B. Freeman, B.E., Graduate. In the discussion, to which Dr. A. Boyd and Messrs. J. E. Morwood, H. B. Marks, A. P. Douglas, A. S. Faulkner, and J. S. Just contributed, it was pointed out that, with the low traffic density in Australian cities, the independent operation of the intersection signals by vehicle control may increase rather than decrease traffic congestion as compared with the existing manual control. It appeared that the definite time-interval control, if synchronized to suit a predetermined satisfactory average road speed, may more quickly clear the traffic than the vehicle-actuated control independently fixed at each intersection. The question of right-hand turns causing cross-traffic at intersections was discussed; and the advisability, or otherwise, of decreasing the length of the green and increasing the length of the amber signals whilst changing from green to red, was stressed. On the wide streets of Melbourne, where fixed time-signals were in operation, when signals changed from green to red, vehicles frequently encroached upon the pedestrian traffic before pedestrians had time to get clear. The meeting terminated with a vote of thanks to Mr. Freeman, who replied to the discussion.

A social gathering of the Queensland members was held at the Belle Vue Hotel, Brisbane, on the 17th October, 1935. In the absence of Mr. W. M. L'Estrange (Local Hon. Secretary), Mr. and Mrs. J. S. Just acted as host and hostess. The gathering was attended by a large number of visitors and representatives of outside bodies.

Western Australia.

At a meeting held at Perth on the 27th August, 1935, a paper was read by Mr. W. G. Forte entitled "An A.C. Method of Iron-Testing." The paper dealt with the development of a satisfactory method of iron-testing using alternating current. The iron sample used for experiments was in the form of laminations, and the method consisted briefly in accurately measuring instantaneous values of B and H at various points of the cycle. No special practicability was claimed for the method, which, the author stated, was best suited to the laboratory. It was pointed out, however, that data obtained under actual a.c. conditions might be more reliable for a.c. calculations than corresponding information from d.c. tests.

Ceylon

At a meeting arranged by the Local Committee and held at Colombo on the 2nd November, 1935, Major C. H. Brazel, M.C., in the chair, a paper by Mr. D. S. Weerasena entitled "The Existing Systems of Telephone Communication in Ceylon" was read and discussed. Among those who took part in the discussion were Messrs. K. V. Alagaratnam, D. P. Bennett, J. K. J. Brown, D. H. Dias, G. L. Kirk (Hon. Secretary), S. W. Peiris, S. Rajanayagam, E. H. Targett, and —. Wijetilleka. The attendance was 25 members and visitors.

The second Annual General Meeting of the Institution members in Ceylon was held at Colombo on the 15th February, 1936, Major Brazel in the chair. The meeting first took the form of a reception at which the Hon. Secretary introduced the members and guests to the Chairman. The reception was followed by a formal meeting and at the conclusion of this the Annual Dinner took place, at which the Chairman delivered an Address. In this he reviewed the activities of the Committee during the past year and also referred to the progress made by the Colombo Electricity Department.

China

At a meeting of the China Centre held at Shanghai on the 28th October, 1935, being the first meeting arranged in conjunction with the Engineering Society of China and the Shanghai Branch of the Institution of Civil Engineers, Mr. J. Haynes Wilson presided and 63 members and guests were present. A paper by Mr. L. B. S. Golds, entitled "Electrical Standardization in Shanghai," was

read and was followed by a discussion in which the following took part: Messrs. E. Jacobs, J. Haynes Wilson, H. E. Crowcroft, A. C. C. Moore, and J. T. Rogers.

Another meeting of the same bodies was held at Shanghai on the 25th November, 1935, when a paper by Mr. P. H. Spagnoletti, B.A., entitled "Acoustic Problems," was read and discussed. Fifty members and guests were present.

A further meeting of the same bodies was held at Shanghai on the 16th December, 1935, 45 members and guests being present. Mr. A. J. Percival was in the chair. A paper by Mr. J. T. Rogers, entitled "The Development of the Modern Telephone Cable," was read and was illustrated by the aid of an epidiascope. As there was no time for a discussion, the meeting terminated with a vote of thanks to the author.

India

Bombay.

A meeting arranged by the Local Committee was held on the 10th December, 1935, at which Mr. S. E. Povey delivered an address on "The Training of an Electrical Engineer in India." The meeting was attended by 105 members and guests.

Meetings were also held on the 18th February and the 10th March, 1936, at which the following papers were read:—

18th Feb. E. G. Lazarus: "The Design of Substations for Indian Conditions."

10th Mar. K. M. Rau: "Some Notes on Electric Lighting and Power Installations in Railway Station Colonies."

Calcutta.

A discussion on "Overhead Line Construction" took place at a meeting arranged by the Local Committee and held on the 18th December, 1935. The discussion was opened by Mr. A. F. Coventry, B.Sc., Associate, who illustrated his remarks with a film.

At a further meeting held on the 22nd January, 1936, the paper by Messrs. E. B. Wedmore, Member, and W. S. Flight, Associate Member, entitled "Voltage Variation at Consumers' Terminals" (*see* vol. 76, p. 685) and also the paper by Mr. F. S. Naylor, Associate Member, entitled "Loss of Revenue due to Poor Voltage Regulation on Heating and Lighting Loads" (see vol. 79, p. 33), were read and discussed.

A further meeting was held on the 19th February, 1936, at which Mr. W. H. Adcock, Associate Member, read a paper entitled "Building Illumination."

A visit took place on the 6th March, 1936, to the Southern generating station of the Calcutta Electric Supply Corporation, Ltd., and a conversazione was subsequently held in the grounds of the generating station. The Chairman of the Local Committee, Mr. F. T. Homan, received the members and guests. The total attendance was 72 and the function was very successful.


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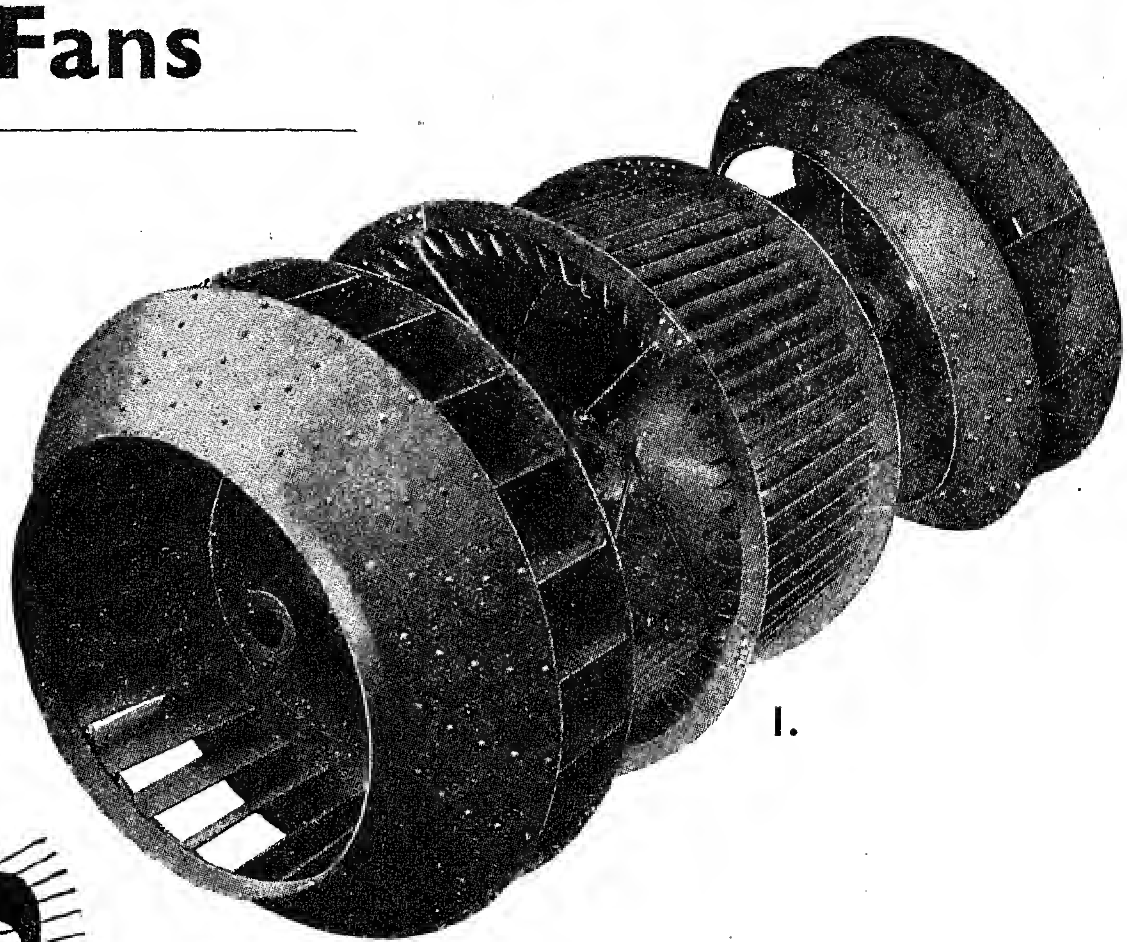

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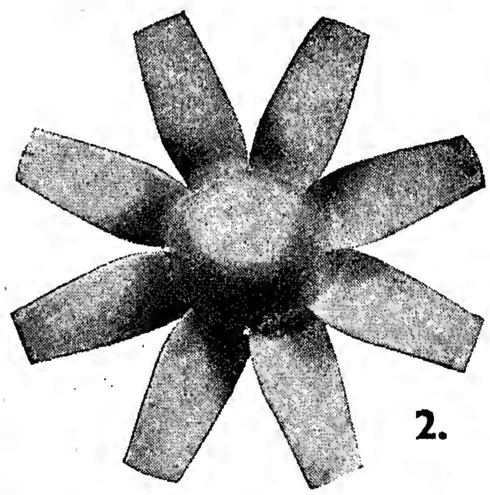

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